CONSULTANT REPORT

PIER
Public Interest Energy Research
CALIFORNIA ENERGY COMMISSION

Environmentally Preferred Advanced Generation

75-KW MOLTEN CARBONATE FUEL CELL STACK VERIFICATION TEST

Gray Davis, *Governor*

APRIL 2000

CALIFORNIA ENERGY COMMISSION

RESOURCES AGENCY

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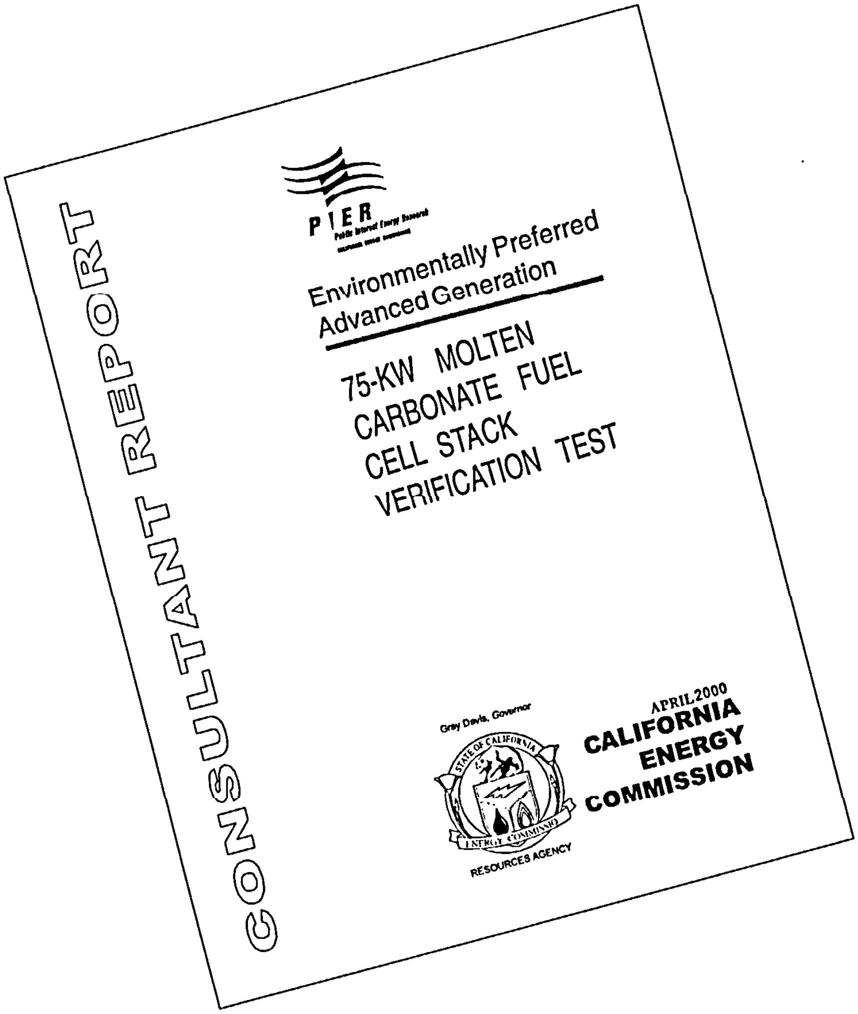

CALIFORNIA ENERGY COMMISSION

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Legal Notice

Acknowledgements

M-C Power would like to thank the other project team members who have been involved with this project and the long term goal of commercializing this technology. Specifically, M-C Power would like to thank the following corporations for their input into this project and the overall commercialization program.

- Alternate Energy Systems Consulting, Inc.
- Bechtel Corporation
- Institute of Gas Technology
- Ishikawajima-Harima Heavy Industries Company, Ltd
- San Diego Gas & Electric Company
- Stewart & Stevenson Services, Inc.

M-C Power would also like to thank the United States Marines for allowing the demonstration to take place at the Marine Corps Air Station Miramar in San Diego.

M-C Power would also like to extend a special thanks to the California Energy Commission for committing the funds to M-C Power as part of Commission's Public Interest Energy Research (PIER) Program, to build and operate this power plant.

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following six RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research.

What follows is the final report for the MC Power, conducted by the M-C Power Corporation. The report is entitled 75-k Molten Carbonate Fuel Cell Stack Verification Test. This project contributes to the Environmentally Preferred Advanced Generation program.

For more information on the PIER Program, please visit the Commission's Web site at: http://www.energy.ca.gov/research/index.html or contact the Commission's Publications Unit at 916-654-5200.

Executive Summary

In 1998, the California Energy Commission, through its First General Solicitation, awarded $1.0 million to M-C Power for a 75-kW MCFC Stack Verification Project. M-C Power completed the testing of a 75-kW Molten Carbonate Fuel Cell (MCFC) at the Marine Corps Air Station Miramar in San Diego, California. This project was partially funded by the California Energy Commission (Commission) under Commission Contract No. 500-97-039 and the Department of Energy (DOE) under DOE Cooperative Agreement No. DE-FC21-95MC30133.

M-C Power demonstrated the performance of an advanced design MCFC 75-kW stack using full size cells under field conditions. Under the Commission Contract, M-C Power modified the existing balance of plant (BOP), which was originally designed for operating with a 250-kW stack. The modifications were made to allow Stack MCP-8, a 75-kW stack, to operate at the plant and to install more reliable BOP equipment based on lessons learned from the operation of previous stacks. All of the modifications were checked and a hot test was conducted without the fuel cell stack to verify the functional operation of the BOP equipment, instrumentation, and control system.

M-C Power assembled and conditioned a 75-kW stack using components manufactured prior to the inception of this contract. After successfully verifying the performance of the stack during conditioning, the stack was packaged and shipped to the Miramar job site, where the stack was installed in a pressure vessel and integrated with the BOP to form the power plant.

This final report covers the 75-kW MCFC Stack Verification project conducted by M-C Power Corporation. This project contributes to the Public Interest Energy Research (PIER) program subject area environmentally-preferred advanced generation.

The project discussed herein was to verify improvements and modifications made to the pressurized, integrated molten carbonate fuel cell (MCFC) power plant located at the Marine Corps Air Station (Miramar) located in Miramar, San Diego, California and to assemble, condition, and operate a 75-kW stack.

The project was structured into three major tasks with associated subtasks:

- Task 1 Project Startup Tasks.
  - Task 1.1 Attend Kickoff Meeting.
  - Task 1.2 Document Matching Funds.
  - Task 1.3 Identify Required Permits.
  - Task 1.4 Obtain Required Permits.
- Task 2 Technical Tasks.
  - Task 2.1 MCFC Stack Assembly and Conditioning.
  - Task 2.2 Plant Modifications.
  - Task 2.3 MCFC Power Plant Startup.
  - Task 2.4 MCFC Plant Operation and Testing.
  - Task 2.5 Production Readiness Plan.

- Task 3 Reporting Tasks.
  - Task 3.1 Monthly Progress Reports.
  - Task 3.2 Final Report.
  - Task 3.3 Final Meeting.

Goals

The overall goal of this project is to demonstrate the performance of advanced design MCFC stack components in a 75-kW electric power generator. The project addresses the PIER program objective of reducing environmental and public health risks of California's electricity by developing electric generating technology that emits no ozone and reduced levels of smog precursor pollutants and carbon dioxide. This project also contributes to the PIER Program's objective of improving electrical system reliability by demonstrating fuel cell technology for distributed electric generating applications.

The overall technical goals of this project were:

- To verify the performance of M-C Power's most advanced stack design in full size cells under field conditions.
- To evaluate the effect of anode recycling on generator performance
- To gather operating data which can be used to base the design of future commercial prototype MCFC generators.

Objectives

The specific, technical objectives upon which this project's success has been evaluated were:

- To operate the 75-kW MCFC Miramar Test Facility at a current density of 110 mA/cm^2 for at least 2000 hours.
- To operate the 75-kW MCFC Miramar Test Facility at a current density of 160 mA/cm^2 for at least 1000 hours.
- To maintain a pressure differential between the anode inlet and the cathode outlet of less than 12 inches water gage.
- To perform at 54 percent efficiency (LHV), including credit for steam fed to the Miramar steam loop.
- To emit less than 5 ppm of Nitrogen Oxide (NO_x)
- To emit less than 5 percent Carbon Monoxide (CO_2)

The overall economic/cost objectives of this project were:

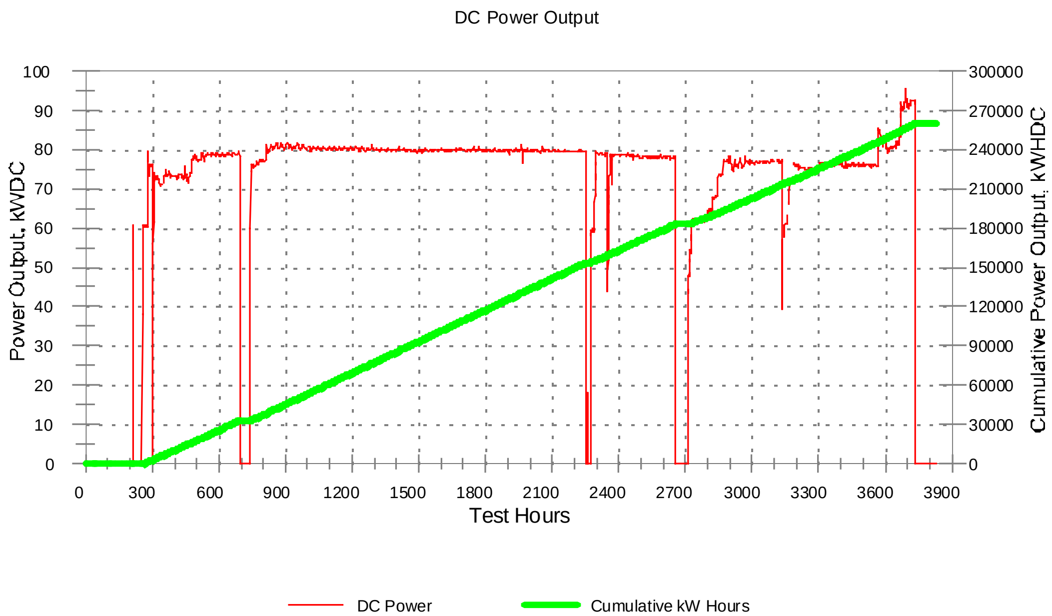
- The total installed cost projection in the range of $1,300/kW to $1,500/kW.
- The projected cost of electricity in the range of $0.05/kWh to $0.07/kWh.

Outcomes

The overall technical goals were met. Achieving these goals involved modification of the Miramar power plant, originally designed to operate with a 250-kW stack, to operate with a 75-kW stack as well as assembly, conditioning, and acceptance testing of the stack, followed by shipment, installation, and startup at the site and performance verification.

The stack assembly and conditioning were successfully performed according to plan. The stack was acceptance tested and generated 44 kW, above the minimum acceptable 37 kW for qualification for shipment.

The stack was installed in the modified power plant which was operated for more than 3,000 hours (5.3 months) and generated 260 MW-hrs as shown in the figure. Anode recycle improved stack performance and power plant output. Emissions data confirm the benefit of fuel cell technology.



M-C Power completed a detailed production readiness report that was submitted as a deliverable to Commission. This report explains in detail the steps M-C Power has taken, or plans to implement, in order for M-C Power to be capable of meeting expected future production demands. Facilities are in place and operational for production of 4 MW / yr Additional equipment is in place for 28 MW / yr starting in 2002.

Conclusions

M-C Power's stack and power plant designs and procedures have been demonstrated for more than 3,000 hours at rated power under field conditions. Both the stack and power plant components performed satisfactorily.

Manufacturing facilities are in place and operational for production of 4 MW / yr and additional equipment is in place for 28 MW / yr starting in 2002. M-C Power stack manufacturing facility plans are in progress for commercial manufacturing in accordance with commercialization plans.

Recommendations

Longer term steady-state testing is needed to establish the durability of the power plant components and of the stack. Additional testing should include an assessment of the system dynamics.

Additional evaluation of anode recycle is warranted. Although initial short tests gave promising results, long-term effects, if any, have not been established.

The power plant and stack should be restarted if additional support is secured. This will provide additional operating data and data on the thermal cycling ability of the stack.

Abstract

M-C Power completed the testing of a 75-kW Molten Carbonate Fuel Cell (MCFC) at the Marine Corps Air Station Miramar in San Diego, California. This project was partially funded by the California Energy Commission (Commission) under Commission Contract No. 500-97-039 and the Department of Energy (DOE) under DOE Cooperative Agreement No DE-FC21-95MC30133.

M-C Power demonstrated the performance of an advanced design MCFC 75-kW stack using full size cells under field conditions. Under the Commission Contract, M-C Power modified the existing balance of plant (BOP), which was originally designed for operating with a 250-kW stack. The modifications were made to allow Stack MCP-8, a 75-kW stack, to operate at the plant and to install more reliable BOP equipment based on lessons learned from the operation of previous stacks. All of the modifications were checked and a hot test was conducted without the fuel cell stack to verify the functional operation of the BOP equipment, instrumentation, and control system.

M-C Power assembled and conditioned a 75-kW stack using components manufactured prior to the inception of this contract. After successfully verifying the performance of the stack during conditioning, the stack was packaged and shipped to the Miramar job site, where the stack was installed in a pressure vessel and integrated with the BOP to form the power plant.

After completing the installation of the stack, the power plant was started up according to the test plan developed for the operation of this stack. The stack operated for over 3800 hours prior to being shutdown in December 1999. During this time the power plant produced over 260 MW-hours of power. The power plant had limited emissions all within recommended ranges, with the exception of carbon dioxide, which is explained by the off-design operating point.

M-C Power gathered and analyzed significant amounts of data during the operation of the stack, which has been summarized and is contained within this report. Essentially, this project verified the performance of M-C Power’s latest stack design under field conditions.

In addition to the power plant operation, M-C Power also prepared a Production Readiness Plan which showed that manufacturing facilities are in place and operational for production of 4 MW/yr and additional equipment is in place for 28 MW/yr starting in 2002. M-C Power stack manufacturing facility plans are in progress for commercial manufacturing in accordance with commercialization plans.

1.0 Introduction

1.1 Background Information

The potential of the electrochemical technology of fuel cells to produce electricity more efficiently and with low environmental impact has been well documented. The Molten Carbonate Fuel Cell (MCFC) technology being developed by M-C Power has distinct advantages compared to other types of fuel cells and other MCFC designs. To make the potential of fuel cells a reality, M-C Power has been conducting a comprehensive program to improve performance and reliability and to reduce costs of the MCFC stack and other components comprising the complete power generation system.

In the 1970s, the Institute of Gas Technology (IGT) conducted research on several fuel cell technologies and demonstrated a practical way to build fuel cell stacks with commercially available materials. M-C Power was established in 1987 to commercialize MCFC technology developed by IGT. Since 1987, M-C Power has advanced the MCFC technology from small laboratory test stacks to a full size field test of fully integrated power system.

During September 30, 1992 through March 31, 1997, M-C Power designed, fabricated, installed, tested, and evaluated a 250 kW Proof-of-Concept MCFC stack in an integrated power plant system at the Naval Air Stations Miramar (Miramar), located in San Diego, California. This project produced many significant accomplishments that advanced the MCFC design towards commercialization.

In June 1998, the California Energy Commission (Commission) selected the M-C Power project (75 kW MCFC Stack Verification Test). M-C Power had submitted this project proposal to the Commission in response to the Commission's Public Interest Energy Research (PIER) General I Solicitation.

The 75-kW MCFC Stack Verification Test conducted at the existing test facility at the Marine Corps Air Station Miramar in San Diego is an important step toward commercializing MCFC power generation technology.

The 75 kW Test Project is part of the MCFC Product Design and Improvement (PDI) program funded by the U.S. Department of Energy (DOE) under Cooperative Agreement No. DE-FC21-95MC30133 and thus is supported jointly by M-C Power and DOE under that Cooperative Agreement. Of the total budgeted cost of the Project, M-C Power and DOE contributed about 76 percent and the PIER Program funded about 24 percent. The dollar amounts are:

- M-C Power / DOE: $3,147,443
- Commission / PIER Program: $1,000,000
- Total Project: $4,147,443

1.1.1 Technology Concept

MCFCs operate at a nominal temperature of 650^{0}C (1200^{0}F) where the potential power of the electrochemical reaction is near its optimum. This temperature is close to the temperature of steam reforming of natural gas, which makes system integration easier. Operating at this temperature also allows the recovery of excess heat as high quality by-product steam and / or hot water which further improves overall process efficiency. Furthermore, carbon monoxide (CO), which is a significant product of the reforming process, is a fuel in a MCFC whereas it is a poison in low temperature fuel cells.

Research performed by IGT also demonstrated a practical way to build a fuel cell stack with commercially available materials. The necessary uniform gas distribution across electrodes was achieved by a concept known as IMHEX® that stands for Internally Manifolded Heat Exchanger. All of the gas streams, anode feed / exhaust and cathode feed / exhaust, flow in manifolds confined within the stack. Seals are incorporated on the surface of the separator plates of each cell around the perimeter of the manifold openings and the plates. This prevents gas mixing and gas leaks. Only vertical clamping forces are needed to maintain these seals.

1.1.2 Technology Need

The basic concept of the fuel cell has been known over 150 years. The use of fuel cells in the space program showed their potential to operate at very high efficiency with virtually no pollution. Now, advances in materials and other technology, coupled with rising energy prices and environmental concerns, have given fuel cells the opportunity to become a practical alternative power source for terrestrial applications.

At the time of M-C Power's formation, the MCFC technology had been demonstrated in the laboratory in a 1000 cm^2 (1 ft^2) cell size in stacks up to 20 cells. The power density was 110 watts per square foot. It was clear from the onset that development work needed to focused on three main areas: increased cell size, increased power density, and reduced cell component costs. Another primary development task identified was the need to design an integrated system incorporating the fuel cell stack with fuel processing, power conditioning and other equipment plus instrumentation and controls to constitute a complete, stand-alone power generating unit.

1.1.3 Purpose of the Report

The purpose of this report is to document all of the work and test results associated with the preparation, installation and demonstration of an advanced design 75-kW MCFC along with the balance of plant (BOP) equipment, which constitutes the power generation system.

1.1.4 Project Goals and Objectives

The overall goal of this project is to demonstrate the performance of advanced design MCFC stack components in a 75-kW electric power generator. The project addresses the PIER program objective of reducing environmental and public health risks of California's electricity by developing electric generating technology that emits no ozone and reduced levels of smog precursor pollutants and carbon dioxide. This project also contributes to the PIER Program's objective of improving electrical system reliability by demonstrating fuel cell technology for distributed electric generating applications.

The overall technical goals of this project are:

- To verify the performance of M-C Power's most advanced stack design in full size cells under field conditions.
- To evaluate the effect of anode recycling on generator performance

- To gather operating data which can be used to base the design of future commercial prototype MCFC generators.

Objectives

The specific, technical objectives upon which this project's success has been evaluated are:

- To operate the 75-kW MCFC Miramar Test Facility at a current density of 110 mA/cm^2 for at least 2000 hours.
- To operate the 75-kW MCFC Miramar Test Facility at a current density of 160 mA/cm^2 for at least 1000 hours.
- To maintain a pressure differential between the anode inlet and the cathode outlet of less than 12 inches water gage.
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The overall economic/cost objectives of this project are:

- The total installed cost projection in the range of $1,300/kW to $1,500/kW.
- The projected cost of electricity in the range of $0.05/kWh to $0.07/kWh.

1.1.5 Project Need

To reach its goal of commercializing the MCFC technology, M-C Power established a long-term development plan. This project is called the "75 kW MCFC Stack Verification Test Project" and it is an important step in M-C Power's comprehensive plan for commercializing MCFC power generation technology in the year 2002. Through this project, M-C Power has verified the power production capability and other performance characteristics of advanced cell components and stack design in a full size power generation field application.

1.1.6 Contributions to Technology Advancement

The reason this project was done now is that it eminently fulfills the mission of the PIER Program, specifically, to provide California's citizens environmentally sound, safe, reliable, and affordable energy services and products. This project also involves energy-related RD&D activities that will advance the MCFC technology for which competitive and regulated markets are not providing adequate funding support. The MCFC Generator being developed is expected to provide the following benefits:

- A 50 percent to 80 percent higher efficiency than conventional combustion type generators with efficiencies ranging between 40 and 50 percent.
- Negligible emissions of ozone and smog precursor pollutants
- Reduced production of carbon dioxide exceeding target of climate change initiatives
- Higher reliability of service which means high quality power, few moving parts, and no transmission lines
- Reduced consumption of fuel resources

- Competitive cost of electricity.

These benefits arise because MCFC technology is fundamentally different from conventional combustion technologies and not subject to the same performance limitations.

Market studies conducted for M-C Power show that customers are interested in having on-site generation with the capabilities and benefits expected from M-C Power's MCFC Generator. Many say they would even pay a premium above their current power costs. A prominent consultant long involved with fuel cells has forecast that the market for MCFC Generators would be as high as 980 MW in 2005 and 3600 MW in 2010. That forecast did not consider the impact of CO_2 emission reduction requirements now being called for to avoid global climate change impacts. Commercial and light industrial businesses were identified as the primary market for fuel cells particularly in states with higher than average electricity rates and not in compliance with air quality standards. The size of the market in individual states was not identified, but because California fits the profile and is a large consumer of power, it is undoubtedly a significant part of the overall market.

1.1.7 Project Approach and Critical Review

The MCFC technology development is a complex process with many associated risks. However, M-C Power is following a program intended to dampen all those risks and increase the probability of success.

The design of the 75 kW stack, which was tested, was preceded by many small-scale tests of the various components. The design exhibiting the greatest promise was then scaled up to full size using M-C Power's experience on previous tests. The scaled-up design is also checked in M-C Power's comprehensive, computerized model of the operation of the stack. The model has been verified by comparing predictions with full-scale test results. Refinements are made as new data become available.

The project is structured with tasks in three areas. Specifically, Task 1, Project Start-Up Tasks, Task 2, Project Technical activities, and Task 3, Reporting Activities. Within the technical tasks, critical project reviews were scheduled after the following tasks to provide the Commission status updates and progress toward the overall goals and objectives.

Subtask 2.1.2: Conditioning and Testing

Subtask 2.2.2: Systems Check-Out

Subtask 2.3.2: Plant Start-Up

Subtask 2.4.1: Test Plan Development

Subtask 2.4.2: Plant Operations and Testing (after 1st month of operations)

1.2 Commission Participation

It is fortuitous that the State of California and the California Energy Commission had the foresight to establish a fund to promote Public Interest Energy Research (PIER). The creation of the fund under the administration of the Commission comes at a time when deregulation and restructuring in both the gas and electric power industries has reduced research funding traditionally available. Research budgets at the utility industry, coordinated research institutions, Electric Power Research Institute and Gas Research Institute, and at individual companies have been reduced. In addition, the focus of the remaining R&D programs has become very short term, i.e., demanding results in under a year. Moreover, the drive by the Federal Government to achieve a balanced budget has caused the DOE to restrict its R&D spending.

As a small business, M-C Power has relied on those traditional sources of support for carrying out its MCFC Generator development work. DOE largely underwrites M-C Power's current commercialization program through a multi-year cooperative agreement extending through the year 2000. Under that agreement (referred to as PDI for Product Design Improvement), M-C Power's cost sharing was about $33 million, and DOE's share was about $71 million. Commission's participation provided funding to assist with the plant modifications at Miramar to support the testing of a 75-kW stack at the Miramar site. The funds from Commission also assisted M-C Power with the assembly, conditioning, testing, shipping, installation, start-up, and operation and data analysis of the 75-kW stack. Commission awarded $1.0.million, through its PIER First General Solicitation, to M-C Power for this project.

1.3 U.S. DOE Participation

The Department of Energy (DOE) has been the key financial resource for the overall development of the Molten Carbonate Fuel Cell commercialization program. The DOE funded the entire cost share ($3,147,443) provided to this Commission contract.

1.4 Other Participants

M-C Power has assembled an excellent team of companies having very well qualified personnel to achieve the objectives of the proposed project. This team has been in place for the past six years and has worked on the design, construction and operation of two 250 kW MCFC demonstrations. They were also working for the design of commercial prototype MCFC Generators. The key members of the M-C Power team for this project included Bechtel, San Diego Gas & Electric Company (SDG&E), and Alternative Energy Systems Consulting (AESC). Bechtel, SDG&E, and AESC are all California-based companies. A brief description of the roles and responsibilities of each team member follows.

M-C Power Corporation

M-C Power installed the equipment for the power plant modifications and performed the systems checkout and hot test. M-C Power Corporation assembled, conditioned, shipped, installed, and operated the stack as well as performing data analysis of power plant operation.

Bechtel

Bechtel performed the design and equipment specification for the power plant modifications. Bechtel also provided technical assistance during power plant startup and operation.

SDG&E

San Diego Gas & Electric (SDG&E) was responsible for all permitting requirements for the project and managed site construction activities. SDG&E maintained the power plant and was involved with making the required modifications for operating and testing the stack for this project.

Alternative Energy Systems Consulting

Alternative Energy Systems Consulting (AESC), a California-based corporation, has extensive knowledge of the alternative energy field. AESC has been part of M-C Power's team for the previous two 250 kW MCFC power plants at Unocal and Miramar. AESC was responsible for the environmental testing and provided logistical support during operations.

2.0 Fuel Cell Stack Development and Demonstration

The details of the work done under this contract are summarized as follows.

2.1 Overall Project Goals

The overall goal of this project was to demonstrate the performance of advanced design Molten Carbonate Fuel Cell (MCFC) stack components in a 75-kW electric power generator. The project addresses the PIER program objective of reducing environmental and public health risks of California's electricity by developing electric generating technology that emits no ozone and reduced levels of smog precursor pollutants and carbon dioxide. This project also contributes to the PIER Program's objective of improving electrical system reliability by demonstrating fuel cell technology for distributed electric generating applications.

The overall technical goals of this project were:

- To verify the performance of M-C Power's most advanced stack design in full size cells under field conditions.
- To evaluate the effect of anode recycling on generator performance.
- To gather operating data to be used as the basis for the design of future commercial prototype MCFC generators.

2.2 Stack Assembly and Shipping

2.2.1 Objectives

The objective of this task was to assemble a 75-kW stack using components manufactured prior to the inception of the Commission contract.

2.2.2 Outcomes

M-C Power completed bipolar plate sub-assembly work on January 11, 1999. Final Stack MCP-8 assembly began on January 12, 1999 and was completed on January 25, 1999 according to the Stack MCP-8 Acceptance Specifications Document. Specifically, Table 1 summarizes the specifications and the actual data collected.

Table 1. Stack Assembly Specifications Summary & Results

Specification Description	Specification	Observations / Notes
Minimum force on wet seal rails with a 40 psi stack clamping force.	>20 psi	Stack meets specifications.
Active area contact area and applied force. Stack clamping force: 40 psi.	≥80% active area contact with 10 psi	Stack not within spec. Expected to conform at operating temperature.
Plate edge alignment.	< 1.6 mm	Stack meets specifications.
Measurement length from face of anode end plate to bottom face of top clamp plate.	< 3.5 mm	Stack meets specifications.
Maximum difference in stack height at the four corners and four midpoint locations.	± 0.25% of measured average	Stack meets specifications.
Quadrilateral Integrity	± 1° of vertical	Stack meets specifications.
Visual gap between active area components.	< 0.5 mm	Stack meets specifications.
Anode to cathode, anode to atmosphere, and cathode to atmosphere dry seal leakage rate.	< 0.3 standard liters/min/cell at 10" water column differential	To be determined during conditioning.

M-C Power took several pictures using a digital camera throughout the entire assembly process. Figures 1 through 3, shown in chronological order, document the final assembly.

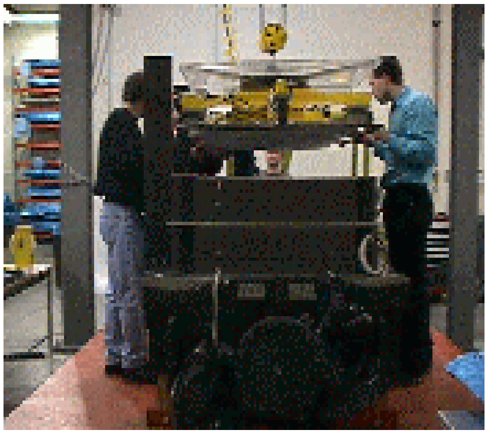

Figure 1. Assembly of the 75kW Stack

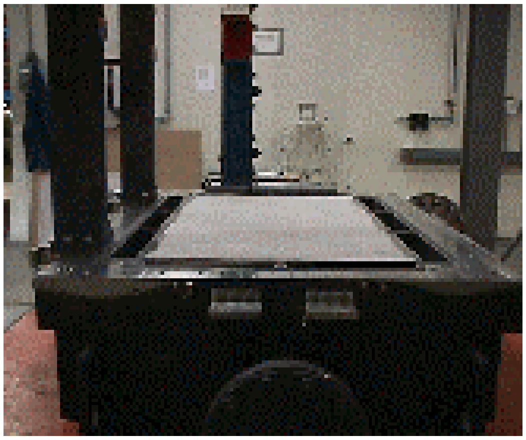

Figure 2. Plenum & Anode End Plate at Start of Assembly

2.2.3 Conclusions

M-C Power's assembly and shipping procedures were proven. The assembled stack met all critical specifications and the stack arrived at the site undamaged.

2.2.4 Recommendations

The assembly and shipping procedures that proved successful with Stack MCP-8 should be used in the future, being modified for special situations.

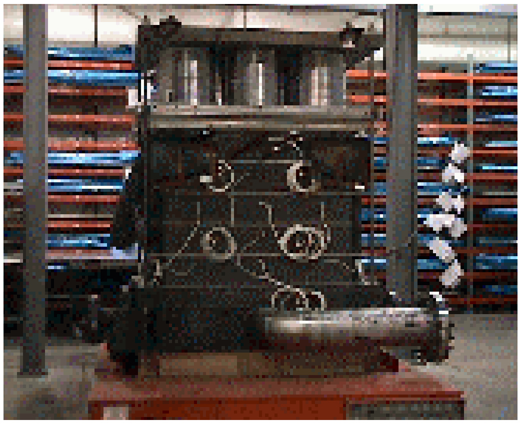

Figure 3. Complete Assembled Stack Ready to be Tested

2.3 Stack Conditioning and Testing

2.3.1 Objectives

The objective of this task was to condition and test the assembled stack in M-C Power's Acceptance Test Facility (ATF) prior to shipping the stack to Miramar.

2.3.2 Outcomes

M-C Power moved the stack from the dry room, where the stack was assembled, to the acceptance test facility on February 3, 1999. During the next week and a half, the stack was installed in the ATF, and all of the necessary activities (instrumentation, furnace installation, insulation work, etc.) were completed in preparation of stack conditioning. Figures 4 through 7 are included for reference showing the movement of the stack from the assembly area (dry room) to the ATF, and some of the ATF installation related activities.

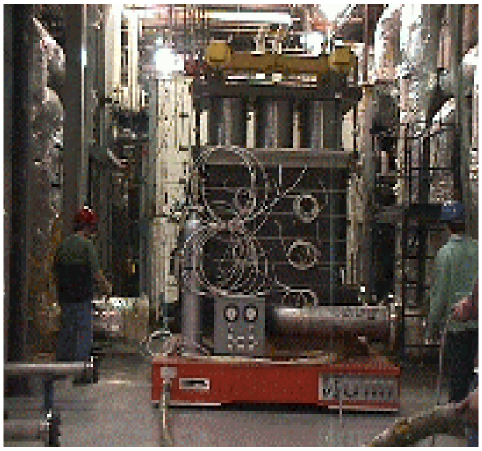

Figure 4. Stack Being Moved on Air Cart from Dry Room to ATF

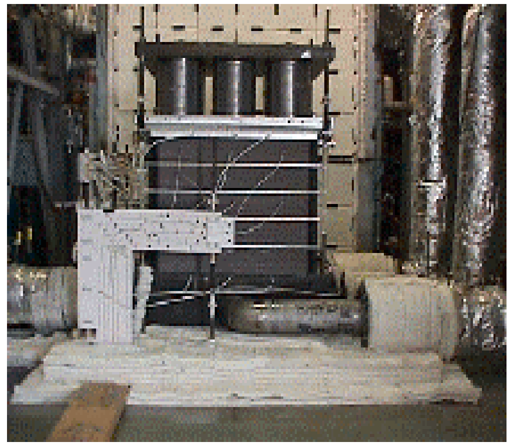

Figure 5. Stack Connected in ATF with Some Insulation Work Shown

Stack conditioning started on Monday, February 15, 1999, with the binder removal phase of conditioning. After the completion of binder removal, the temperature was ramped upward to start the electrolyte melting phase of conditioning. This phase was completed successfully.

Figure 6. Stack Enclosed in the Furnace

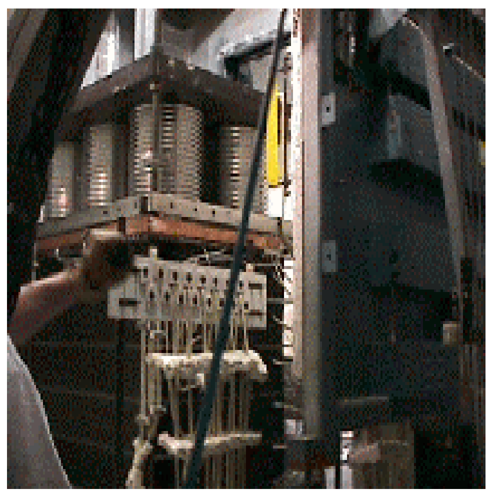

Figure 7. Furnace Wall Being Installed Around the Stack

After the electrolyte melting phase of conditioning was completed, adjustments were made to increase the temperature of the stack to roughly 570°C for cathode oxidation, the final phase of conditioning.

After completing the cathode oxidation phase of conditioning on February 28, 1999, appropriate changes were made to increase the temperature and change the process gases to operate the stack with a load to complete the acceptance test. The stack operated for over 160 hours under load during acceptance testing. Power output of the stack during operation was over 44 kW compared to the minimum acceptable output of 37 kW at the test load conditions in the ATF. Stack leak testing was completed by tracking the wet seal efficiencies at manifold over pressure conditions. Analysis of the leak testing results indicated a definite increase in anode sealing of this stack compared to the available data from the operation of previous stacks.

M-C Power developed an “Operational Acceptance Specification” which was used to qualify this stack. Table 2, Operational Acceptance Specifications and Actual Values, was prepared to summarize the issued specifications and the actual values obtained during the acceptance test of this stack assembly.

All of the specifications were met with the exception of the cell package voltage uniformity and the maximum anode pressure drop. M-C Power personnel reviewed the deviations from these two specifications and concluded that the deviations would not adversely impact the stack’s field operation or performance. Consequently, the stack was released for shipment to Miramar. The stack began cooling down on March 10, 1999 and reached ambient temperature on March 16, 1999. Preparations were made for the removal, packaging, and shipment of the stack to Miramar.

Table 2. Operational Acceptance Specifications and Actual Values

Specification Description	Specification	Value Obtained
Minimum stack voltage at a test load of 400 ADC(1) with facility gas flows: Anode: H_2 1300 slm(2), CO_2 324 slm, N_2 1000 slm, H_2O 405 slm Cathode: Air 1960 slm, CO_2 840 slm, Recycle 8000 slm	93.0 VDC(3)	102 VDC
Cell Package Voltage Uniformity	5% at test load 1.5% at open circuit	5.0% at test load 1.8% at open circuit(4)
Maximum anode pressure drop	561×10^{-6} In WC(5)/slm	794×10^{-6} In WC/slm
Maximum cathode pressure drop	561×10^{-6} In WC /slm	378×10^{-6} In WC /slm
Minimum sealing efficiency with anode outlet manifold to cathode outlet manifold pressure.	Anode: 95% Cathode: 95%	Anode: 97% Cathode: 98%
Minimum sealing efficiency with anode outlet manifold 5 InWC > cathode outlet manifold pressure.	Anode: 85% Cathode: 95%	Anode: 94% Cathode: 98%
Minimum sealing efficiency with cathode outlet manifold 5 InWC > anode outlet manifold pressure.	Anode: 95% Cathode: 85%	Anode: 97% Cathode: 94%

(1) ADC = amps direct current
(2) slm = standard liters per minute
(3) VDC = Volt Direct Current
(4) Specification not met but no adverse impact on performance
(5) InWC = inches water column pressure

A brief write-up describing these specifications follows:

Minimum stack voltage at a test load of 400 Amps direct current

This specification assigns a quantitative acceptance criteria of acceptable stack voltage at a defined current load. The basis for this minimum voltage value is review of stack performance achieved during acceptance tests conducted on previous stacks, subscale testing for evaluation of standard ATF performance levels, and model performance analysis and application of known scale up effects. This standard should be applied after stable operation is achieved.

Voltage Uniformity

This specification applies to the average cell voltage of the twelve configured cell package measurement voltages (five to ten cells each) provided for evaluation of stack performance during acceptance testing and power plant operation. The average cell voltage of each cell package measurement can be compared to the average cell voltage calculated from the total stack voltage measurement. The values chosen define the level of expected relative cell performance, which is dependent upon the uniformity of active area component operation, stack / cell gas distribution, and internal stack temperature distribution.

Maximum anode pressure drop

This specification defines the maximum manifold-to-manifold allowable anode pressure drop per flow rate. This specification is based upon the design analysis completed during the cell / stack design phase and has not been empirically verified at full area scale. In setting the value, the recommended 20 percent safety factor from the design analysis was employed.

Maximum cathode pressure drop

This specification defines the maximum manifold-to-manifold allowable cathode pressure drop per flow rate. This specification is based upon the design analysis completed during the cell / stack design phase and has not been empirically verified at full area scale. In setting the value, the recommended 20 percent safety factor from the design analysis was employed.

Minimum Gas Sealing Efficiency

These specifications define, based upon a static differential pressure method, the minimum level of initial gas sealing for the fuel cell stack before being placed into service. This specification is based upon analysis of the gas sealing obtained during ATF operation of previous stacks prior to field deployment.

2.3.3 Conclusions

The stack met all of the pertinent specifications with the exceptions noted in Table 2 (cell package voltage uniformity and maximum anode pressure drop) and the stack was accepted for shipment to Miramar.

2.3.4 Recommendations

Because of the success of this task, M-C Power should continue using the established stack conditioning and acceptance procedures.

2.4 Miramar Plant Modifications and Hot Test

2.4.1 Objectives

The objective of this task was to modify the existing balance of plant (BOP), originally designed and operated with a 250-kW stack at the Marine Corps Air Station Miramar (Miramar), to accept and operate a 75-kW stack. The hot test was conducted to verify the operation of all the mechanical, electrical, and control systems over the entire operating envelope without the fuel cell stack.

2.4.2 Outcomes

M-C Power coordinated all of the planned plant modifications to accommodate the operation of a 75-kW MCFC stack at the Miramar facility. The following list shows all of the modifications completed.

Description of Modification

- New liquid nitrogen valve
- Improved turbocharger
- Permanent oil / water separator for turbocharger
- New air compressor as a backup for the turbocharger
- Improved cathode recycle blower
- Improved sulfur gas chromatography analyzer
- Improved cathode heater control panel
- New cathode bypass loop
- New cathode bypass valve
- New seal pot level switches
- New check valves
- New anode recycle loop
- New heat tracing for GC sample lines
- New trim for natural gas valve
- New boiler feed water pump as a spare
- New load bank as backup to inverter
- Modified inverter

M-C Power completed all of the major plant modifications. After the completion of all the major plant modifications, the following activities were completed.

- Verification of all of the associated electrical power and control wiring terminations.
- Verification of proper rotation of all rotating equipment.
- Pressure leak testing of the power plant.

After verifying the readiness of the power plant to operate, M-C Power conducted a hot test. During the hot test, the power plant operated at system pressure and temperatures while the fuel cell stack process lines were blocked and bypassed.

All of the major equipment tested worked satisfactorily and within rated specifications. Specifically, two pieces of equipment with improved designs, the cathode recycle blower and the turbocharger, demonstrated reliable performance. The cathode recycle blower was re-designed with a smaller impeller to accommodate the lower flow rates for the 75-kW stack. The blower with the revised shaft coating / seal arrangement was successfully hot tested with the seal leakage consistently meeting design limits. The turbocharger with improved design also ran successfully without encountering any of the surges experienced previously during power plant operation.

The overall performance of the power plant during the hot test was satisfactory. Both the newly added cathode bypass loop and anode recycle loop were successfully tested. As a result of this hot test, a few minor improvements were made and some failed instrumentation was corrected prior to the actual operation of the 75-kW stack.

2.4.3 Conclusions

As a result of all of the modifications made and the verification of these changes, it was concluded that the Miramar test facility was correctly modified to accept a 75-kW stack for use as a power plant demonstration.

2.4.4 Recommendations

M-C Power should continue to use power plant operating envelope evaluation procedures and implement modifications as necessary.

2.5 Stack Installation and Start-Up

2.5.1 Objectives

The objective of this task was to install the 75-kW stack at the Miramar test facility and start-up the integrated power plant.

2.5.2 Outcomes

This task was started on Monday May 10, 1999 with the arrival of Stack MCP-8. M-C Power completed several tasks related to the preparation of the pressure vessel base to accept Stack MCP-8, which was removed from the shipping container and installed into the pressure vessel. M-C Power cleaned the bus bar contact areas and cleaned, deburred and prepared all studs and nuts. These studs and nuts were used to connect the four process pipes to the plenum. Next, the insulation was installed around the process pipes in the pressure vessel.

M-C Power worked from a field instrumentation punch list to complete several necessary activities to prepare Stack MCP-8 for operation. M-C Power also completed nozzle work, which involved routing thermocouples to nozzles in such a way as to prevent possible shorting or damage. The installation is shown in Figures 8 through 11.

Figure 8. Working on Stack within Pressure Vessel Base

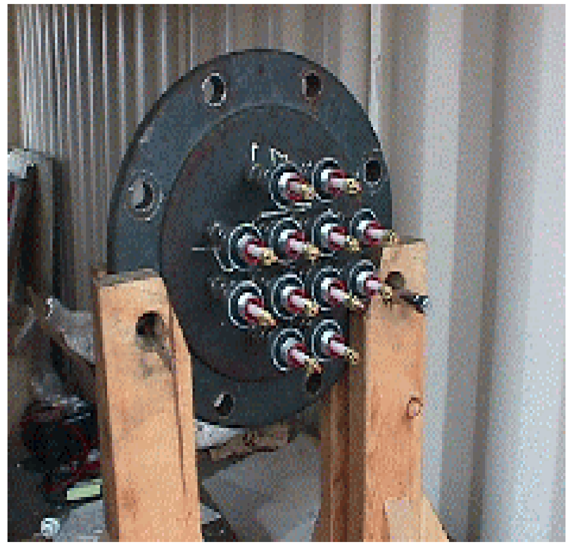

Figure 9. Nozzle Work Completed for Stack MCP-8

Figure 10. Lowering Pressure Vessel Dome over Stack MCP-8

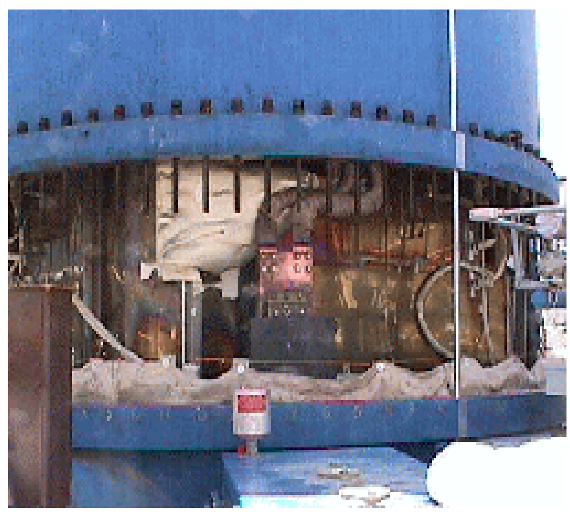

Figure 11. Pressure Vessel Dome just prior to Lowering Dome to the Bottom

Additional work consisted of installing and connecting all of the required voltage leads, verifying all connections with appropriate meters and insulating and isolating all leads and connections as required.

Also, the installation activities included the connection and insulation of the required thermocouples, the installation of the pressure vessel bulk insulation and the installation of the pressure vessel dome. The stack installation activities were completed on June 15, 1999. Some additional balance of plant (BOP) activities and operator training occurred after the installation work was completed and the entire power plant, which includes the stack and the BOP, was ready for operation on Wednesday, June 23, 1999.

Power plant startup began on Wednesday, June 23, 1999 when the Stack MCP-8 heat-up was initiated. The heat-up was accomplished in nine segments as summarized in Table 3 and Figure 12.

A graphical summary of the actual stack temperatures and pressures are shown in the Figures 13 and 14, respectively. The first 213 hours show the temperature changes in various locations during plant start-up. The remainder of the graph shows the temperatures during steady state operation.

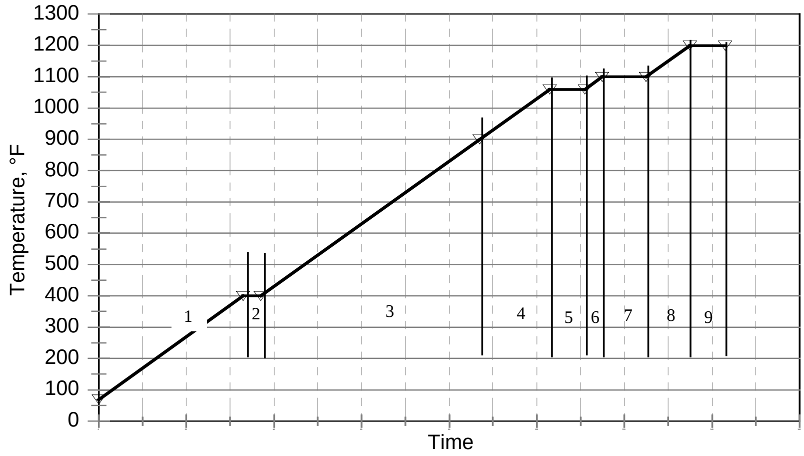

Figure 12. Stack MCP-8 Heatup Schedule at Miramar

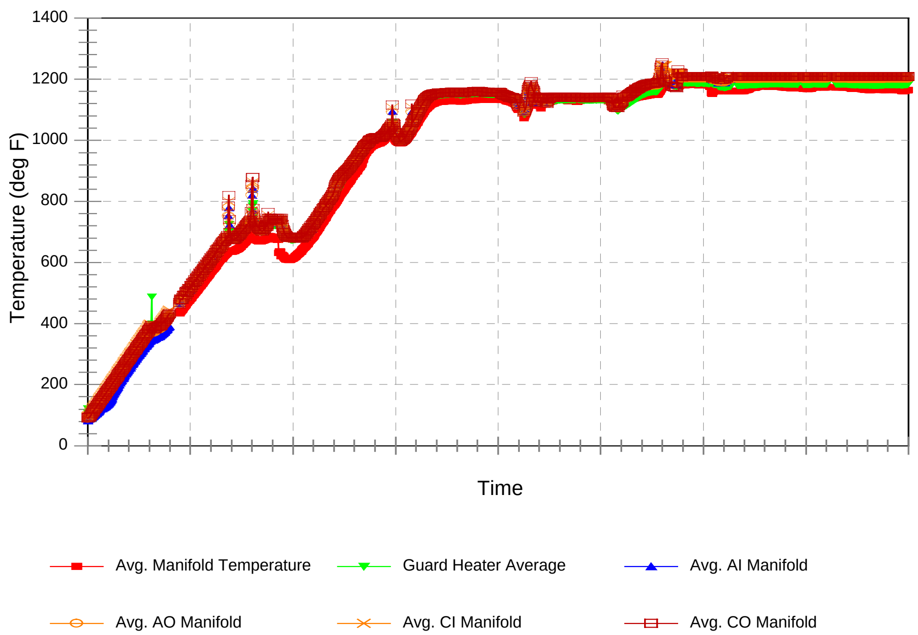

Figure 13. Miramar Stack Temperatures

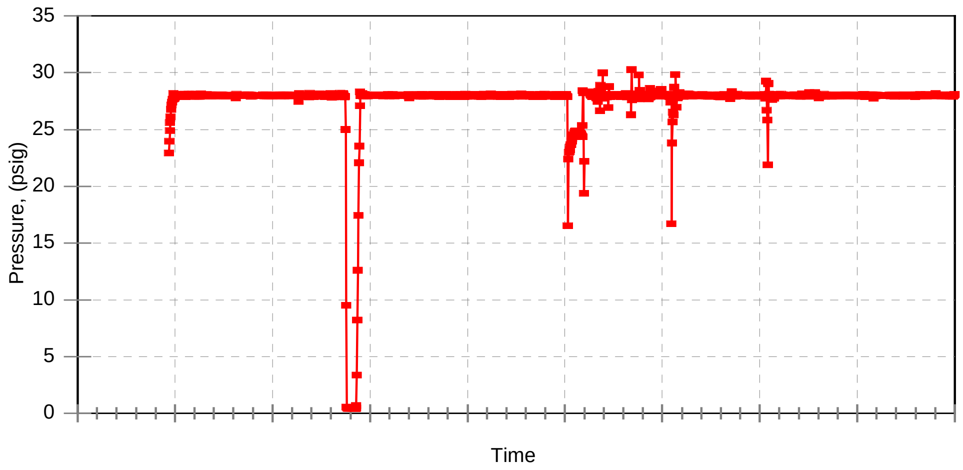

Figure 14. Miramar Cathode Exhaust Gas Pressure

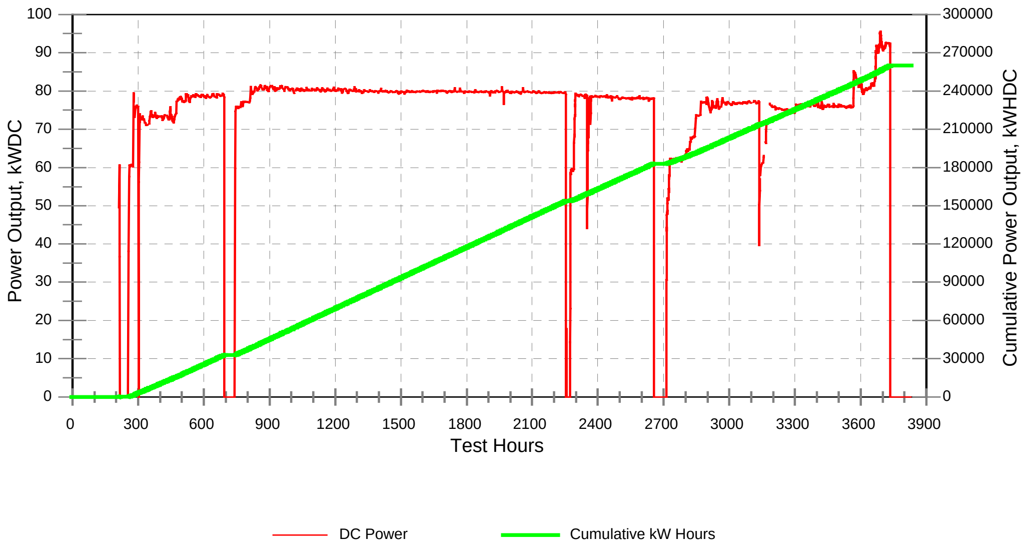

Figure 15. Miramar DC Power Output

2.5.3 Conclusions

The established stack installation and startup procedures were successful.

2.5.4 Recommendations

Established stack installation and startup procedures should continued to be used and modified to accommodate power plant design changes.

2.6 Plant Operations and Testing

2.6.1 Objectives

The objective of this task was to operate the plant for a period of about six months to obtain operating data for verifying the performance of the 75-kW MCFC stack.

Table 3. Startup Plan for the Miramar Power Plant

Plant State No.	State	Segment No.	Temperature Ramps		Gases	
			From °F	To °F	Anode gas	Cathode gas
1	Purge; Pressure	—	70	70	Nitrogen	Nitrogen
2	Heat up to 1100°F	1	70	400	Nitrogen	Nitrogen
		2	400	400	$97N_2/3H_2$	Nitrogen
		3	400	900	$97N_2/3H_2$	Nitrogen
	Melting	4	900	1060	Inert	Inert
		5	1060	1060	Inert	Inert
		6	1060	1100	Inert	Inert
3	Standby	7	1100	1100	Standby fuel	Standby oxidant
		8	1100	1200	Standby fuel	Standby oxidant
4	Initial load	9	1200	1200	Initial load fuel	Initial load oxidant

2.6.2 Outcomes

This task started during the first week of July 1999 with the initiation of the first load on the stack on July 2, 1999. The stack began producing power with an output of 60-kW and within a few days the stack was producing power in the 75-kW to 80-kW range. Figure 15 shows the DC power output since the start of stack heat-up through the end of the test.

As of the end of the test, the stack had operated and produced power as follows:

Test Hours:	3828.75 hrs. (Hours since stack heat-up initiated)
On-Load Oper. Hours:	3354.50 hrs. (Actual hours with load applied)
Total Power Produced:	260.13 MW-hours

Overall, stack temperatures and output have been stable with a few exceptions caused by minor interruptions in the balance of plant (BOP) equipment as described here.

On July 22, 1999 the power plant did not produce power because a turbocharger hose failed. As a result of this failure the turbocharger was taken out of operation and the leaking hose replaced.

On September 25, 1999, there was a power outage at the plant that lasted approximately 40 minutes. After the power outage, while applying a load, the turbocharger began surging and the plant was placed on safe gases. The turbocharger was allowed to cool off overnight and was replaced the following morning. The load was gradually increased to the levels prior to the power outage and the power output reached 79.1-kW on September 28, 1999.

On September 29, 1999, the cathode heater shut down. The cause was determined to be a blown fuse in the heater panel. This blown fuse caused a loss of power to the controls that operate the cathode heater. The bad fuses were replaced and the cathode heater was properly operating again a few hours later. While the cathode heater was out of service, the temperature at the cathode inlet decreased about 10 percent. As a result, the load was gradually lowered and the blower speed lowered to minimize heat loss in the stack. This caused the power output to drop below 50-kW. However, as the load was increased to normal operating ranges, the power output returned to 78.4-kW.

On October 12, 1999, there was a power outage at the plant that lasted approximately 90 minutes. After the power outage, while applying a load, the turbocharger began surging and the plant was placed on safe gases. The turbocharger was replaced before going back on load. The load was gradually increased to the levels prior to the power outage and the power output reached pre-outage levels.

On October 28, 1999, the anode heater shut off for no apparent reason. There was no indication of a trip at the heater control panel. However, after a review of the logic, it appeared that a low flow alarm from a flow meter caused the heater to stop. Appropriate personnel were contacted to confirm the logic and appropriate changes were made to the alarm set points. The stack was returned to normal operating conditions after the logic changes were made.

On November 26, 1999, the power plant was placed in a cool-down mode after 3736 test hours of operation. The stack completed the goal of 3000 hours of operation on load.

2.6.3 Conclusions

The stack operated satisfactorily with the exception of the issues noted above. The original objectives of the test included stack operation at 160 mA/cm2 after operation at 110 mA/cm^2. However, because the stack was already generating 75 kW at the lower current density of 92 mA/cm^2, the decision was made to continue at 92 mA/cm^2 to avoid any unnecessary risk by operating at 160 mA/cm^2. Short runs of higher current density were made at the end of the test.

The total cumulative test time at 92 mA/cm^2 was about 2330 hours and, as expected, the stack voltage distribution became less uniform with increasing operating time and current density.

2.6.4 Recommendations

Future testing should include significant operating time at 160 mA/cm^2 to establish performance and durability characteristics at higher current density.

2.7 Plant Operating and Test Procedures

2.7.1 Objectives

The objective of this task was to develop a comprehensive test plan that established the technical objectives and procedures for the plant operating period.

2.7.2 Outcomes

M-C Power developed, approved, and implemented a detailed test plan for the operation of Stack MCP-8. This stack verification test plan follows.

75 kW MCFC Stack Verification Test Plan

A major step in M-C Power's plan for developing and commercializing its MCFC technology was to assemble an advanced 75-kW MCFC stack and test it at the existing verification test facility at Miramar. This 75-kW Test Project was a follow-up to a 250-kW test run at Miramar in 1997. While there were many important accomplishments in that test, it was evident that design and equipment changes would be necessary to reach commercial performance and cost goals. Based on the test results and ongoing development work, M-C Power identified improvements in the stack design and operating system design for testing at full scale under power plant conditions in this 75-kW Test Project.

Test Description

The goals of this proposed 75 kW Test Project were:

- Verify the performance of M-C Power's most advanced stack design in full size cells under field conditions.
- Evaluate the effect of anode recycle on generator performance.
- Gather operating data upon which to base the design of future commercial prototype generators.

A description of what would be tested relative to each goal and how that would advance the technology toward commercial readiness

Verify Stack Performance: The 75-kW MCFC stack to be tested under this project included several changes to components expected to improve performance (power density and efficiency) and life and to reduce costs compared to the 250-kW stack tested in Miramar in 1997. The changes were prompted by information gained from the 1997 test and from M-C Power's continuing research and development program. Many advances had been made since mid-1995 when the components were selected for the stack to be used at Miramar. Those advances involved changes in materials formulations, manufacturing technologies, and component thickness. The gas flow pattern across the cells has been changed to cross flow from counter flow to reduce pressure differentials at the seals and provide more flexibility in operation.

Each of the changes had been tested in small scale (100 cm^2 and 1000 cm^2) cells and stacks under simulated operating conditions at the testing facilities at M-C Power or the Institute of Gas Technology (IGT). This 75-kW Test Project was necessary to verify that these improvements could be attained at full scale under power plant operating conditions. The 75-

kW Test Project was the first opportunity to test this stack design at full cell size and pressurized operation. The primary test goal was to operate at a current density of 110 mA / cm^2 for at least 2000 hours.

If operation at 110 mA / cm^2 proved successful, the power plant and stack would then be ramped up to 160 mA / cm^2 for 1,000 hours and up to 175 mA / cm^2 for 1,500 hours. The remainder of the test would be at 110 mA / cm^2.

Gather Operating Data: The Miramar Test Facility is highly instrumented and incorporates a data acquisition system that monitors and records 220 operating variables as frequently as every 30 seconds. This data would be gathered during the initial startup, normal operation, anode recycle operation, and transfers from on-line operation to off-line and visa versa. M-C Power also planned to intentionally thermal cycle the stack (cool to atmospheric temperature and return to operating temperature). Operating data recorded before and after this test was vital in determining the effect of thermal cycling on performance.

All data was to be analyzed to identify the impact of each design change tested on improving the commercial viability of the MCFC Generator. The test results would also be compared to the results predicted by M-C Power's design model. Significant discrepancies would be examined further to determine the reason, if possible. The model would be updated as appropriate to make it a more accurate and reliable tool for evaluating proposed design changes in the future.

Emissions measurements would be taken before startup and quarterly thereafter.

Test Objectives

- Demonstrate the state-of-art design of a cross-flow fuel cell stack.
- Demonstrate the performance of a commercial-size Lithium / Sodium (Li / Na) type of fuel cell.
- Test the reliability of hot cathode recycle blower and turbocharger operations.
- Both the cathode recycle blower and the turbocharger will be run prior to fuel cell stack installation to establish their reliability.
- Conduct thermal cycling tests near the end of the 75 kW stack test to assess their effect on the stack pressure drop and stack performance.
- Provide power plant operational data to guide future fuel cell stack and power plant designs.

This 75 kW stack is the first Li / Na fuel cell stack to be tested both in the cross-flow configuration and in the anode recycle mode by M-C Power. It is a prototype stack for the subsequent 250 kW demonstration stacks. The power plant operating data derived from this stack will provide information for guiding the future commercial fuel cell stack and power plant designs.

2.7.3 Conclusions

The Test Plan was effective in defining the test goals, planning the test, and guiding start-up, operations, and shutdown.

2.7.4 Recommendations

Test Plans should continue to be used to document and disseminate test objectives, protocols, goals, and results.

2.8 Plant Data Collection and Analysis

2.8.1 Objectives

The objective of this task was to analyze and interpret data obtained from plant operations. The results of the data analysis will be used for evaluating the performance of the MCFC power plant relative to its expected performance.

2.8.2 Outcomes

M-C Power collected operating data on a daily basis during the operation of the 75-kW stack. The data were used to provide ongoing analysis of stack and power plant operating characteristics such as power output and endurance.

2.8.3 Conclusions

The power plant performance data obtained from the Miramar Power Plant operation per subtask 2.4.3 are summarized as follows. The plant was started up on June 23, 1999 19:00 PST. (i.e. zero test hour) and shut down started on November 26, 1999 (i.e., 3735 test hours) and the cool down was completed on November 30, 1999 (~3830 test hours). The original test plan was to run the 75 kW stack (MCP-8 Stack) at 110 mA/cm^2 current density for 2000 hours and at 160 mA/cm^2 for 1000 hours. However, by running the power plant at about 92 mA/cm^2 current density, the stack dc power output already exceeded 75 kW, and the voltage distribution was not as uniform as expected. Therefore, it was decided to run the power plant at only 92 mA/cm^2 as long as possible, and to make short runs of higher current density operation near the end of the test. The total cumulative test hours at 92 mA/cm^2 was about 2330 hours and, as expected, the stack voltage distribution became less uniform with increasing operating time and current density.

In summary, the 75 kW stack and power plant test at Miramar provided substantial commercial operating data for evaluation. By operating the power plant for a total of about 3735 test hours, the total dc power output was 260 MWhr. Stable operation was demonstrated for a current density level of 92 mA/cm^2. Higher current density operation achieved at the end of the test was 130 mA/cm^2.

Also, in anticipation of future funding, the stack is in cold standby for subsequent testing including testing at higher current density. This is a prudent decision to not accidentally damage the stack at higher current density considering that the stack has already provided the target power output at lower current density.

2.8.4 Recommendations

The stack and power plant should be restarted when additional financing is secured. This will allow continued operation to establish durability and verify the ability of the power plant to withstand thermal cycles.

2.9 Environmental Assessment

This is an environmentally-preferred advanced generation project with an alternate goal of producing MCFC Generators for use in industrial, commercial, and distributed generation applications in the size range of 250 kW to 10 MW. As such, M-C Power understood that the Commission established two alternative stretch goals for this project which were interpreted as follows

This project would strive to reduce the difference between the currently projected price of electricity from an MCFC generator and the average commercial price of electricity by at least 50 percent while maintaining or improving environmental or public health performance. Emissions of criteria pollutants or carbon dioxide from the MCFC Generator should be at least 15 percent below current emissions from gas engines or turbines in the same size range, while maintaining or improving cost performance.

The stretch goal M-C Power was working toward was reduced emissions. A primary benefit of the MCFC technology is that it does not create nitrogen oxides (NO_x) in the process as a combustion system (engine or turbine) does. NO_x emission rates of less than 1 ppm are expected even from the test unit and regardless of load. This is well below the rate currently allowed by regulations. Generally, the best a gas turbine or engine in this size range can achieve is about 10 ppm and most often the actual is higher. Thus, we expect the MCFC to reduce NO_x emissions by 90 percent or more.

MCFC Generators are also very efficient consumers of light hydrocarbons and carbon monoxide. The emissions of these ozone precursor chemicals are expected to be negligible and at least 15 percent below emissions from turbines or engines. In fact, common techniques for reducing NO_x emissions from turbines tend to increase carbon monoxide production.

Because they convert fuel to electricity more efficiently, MCFC Generators will produce less carbon dioxide than engines or turbines. The importance of reducing carbon dioxide production has recently become widely recognized. MCFC Generators will produce much less carbon dioxide than today’s combustion systems because MCFCs convert fuel to electricity more efficiently. Current designs project that commercial MCFC Generators will have an efficiency of 54 percent (LHV). Gas engines and turbines are only 30 percent to 35 percent efficient, and they will produce 50 percent to 80 percent more carbon dioxide per kilowatt hour of power generated than M-C Power’s fuel cell unit. This test is a prelude to a planned full 250-kW test that will fully demonstrate high efficiency operation.

These environmental benefits can be attained at a cost that is commensurate with what a customer of this class would otherwise pay. The Energy Information Administration (EIA), a part of the Department of Energy, forecasts that the average cost of electricity paid by commercial customers in the U.S. in 2005 will be 6.8¢/kWh. Commission reports include that commercial customers in California are paying about 10¢/kW. Commission’s own levelized cost projections for MCFCs are in the ranges 7.3–11.2¢/kWh, 5.5–8.0¢/kWh, and 9.4–20.9¢/kWh depending on type of ownership. M-C Power’s model predicts levelized costs of 5–7¢/kWh based on M-C Power’s projected capital costs for 2005. In addition, power from the MCFC Generator will be of high quality and reliability which is likely to save the customer money by reducing or eliminating interruptions to the customer’s operations or eliminating the need to install and maintain backup power equipment.

On this basis, an environmental assessment (primarily emissions testing) was performed during the 75-kW MCFC operation at the Miramar test site. Details of the emissions testing and results are presented in Appendix I.

2.9.1 Objectives

The objective of this task was to establish baseline emissions data and to collect emission data on a quarterly basis.

2.9.2 Outcomes

During the course of this project, emission data were collected just prior to start-up and two times during the operation of the power plant. The first set of data during operation was taken to establish the sampling procedures. These data were not taken at the correct location for evaluation of the actual emissions from the operating power plant. Therefore, only the second set of emissions data is presented here. A comparison between the emissions data from the Miramar power plant and emissions standards from the San Diego County Air Pollution Control District (SDCAPCD) and the South Coast Air Quality Management District (SCAQMD) is shown in Table 4.

2.9.3 Conclusions

All power plant emissions were within recommended ranges, with the exception of carbon dioxide, explained by the off-design operating point.

2.9.4 Recommendations

M-C Power recommends that emissions continue to be monitored for future power plants, especially power plants operating at rated design power.

Table 4. Emissions Comparison

	NOx (ppm)	CO (ppm)	CO_2 (lb/MMbtu)	NMHC (ppm)	CH4 (ppm)	SO2 (ppm)
Miramar MCFC	0.4	176	124	0.9	146	____
Gas Turbine[1]	42	____	____	____	____	____
Recip I/C >50 bhp[2]						
Rich-Burn	50	____	____	____	____	____
Lean-Burn	125	____	____	____	____	____
Stationary I/C >50 bhp[3]	36	2000	____	250	____	____
NG Combined Cycle[4]	0.042	____	110	____	____	____

1. SDCAPCD Rule 69.3 – Stationary Gas Turbines
2. SDCAPCD Rule 69.4 – Stationary Reciprocating Internal Combustion Engines
3. SCAQMD Rule 1110.2 – Emissions from Gaseous and Liquid-Fueled Engines
4. The Cogeneration Journal – Vol. 6, No. 3, 1991

2.10 Production Readiness Plan

The intent of the Production Readiness Plan was to evaluate the status and capacity of M-C Power's current manufacturing facilities and to establish the requirements for the future. The requirements for the future include capacity requirements for market entry and for the mature market. A future factory layout and capital requirements were developed. A detailed Production Readiness Plan was issued as a deliverable for Task 2.5. This report is attached as Appendix II.

2.10.1 Objectives

The overall objective of this task was to evaluate and demonstrate M-C Power's preparedness to produce a commercially viable product. The specific objectives of this Commercial Manufacturing Readiness Plant were:

- Define production processes for manufacturing of a commercial IMHEX® Molten Carbonate Stack.
- Identify requirements of machines, equipment, manpower, methods, materials, and facilities for manufacturing of a commercial IMHEX® Molten Carbonate Stack.

- Determine capacity constraints imposed by the market for the current design of a commercial IMHEX® Molten Carbonate stack.
- Identify hazardous or non-recyclable materials.
- Establish a projected cost of a commercial IMHEX® Molten Carbonate Stack.
- Establish an implementation plan to fully commercialize the IMHEX® Molten Carbonate Stack.

2.10.2 Outcomes

M-C Power leases three buildings in Burr Ridge, Illinois, a southwest suburb of Chicago (77,000 square feet) which house all of the necessary equipment to produce 4 MW / year of finished MCFC power modules. Anticipated technology and production improvements are expected to triple capacity by the year 2002 when commercial product deliveries begin. New automated manufacturing facilities have been designed and are planned to be built and in operation by 2002 with a power module capacity of 28 MW / year expandable to 84 MW by the year 2005.

Bechtel and Stewart & Stevenson Services, Inc. (S&S) are currently designing commercial prototype BOP requirement. Equipment specifications are under development with key pieces being verified in the Miramar plant following the 75 kW MCFC stack verification test. S&S has fabricated two 250 kW BOP demonstration skids and will market, fabricate, install, and maintain the commercial MCFC power generators in the U.S.

Both DOE and GRI have conducted independent assessments of M-C Power's technology development goals / programs and business plans to determine their credibility and achievability. These assessments have confirmed technology, market, specification, product, and price readiness by the year 2002 when commercial sales will take place.

M-C Power is working with a leading investment banking firm to raise the remaining capital required to complete its commercialization program.

M-C Power completed a detailed Production Readiness Plan, submitted as a deliverable to Commission. This report explains in detail the steps M-C Power has taken, or plans to implement, in order for M-C Power to be capable of meeting expected future production demands.

Facilities are in place and operational for production of 4 MW / yr. Additional equipment is in place for 28 MW / yr starting in 2002.

2.10.3 Conclusions

Execution of M-C Power's stack manufacturing facility plans are in progress for commercial manufacturing in accordance with commercialization plans.

2.10.4 Recommendations

Continued effort is needed to implement plans for commercial manufacturing. Specifically, site selection has not been fully considered. M-C Power should raise the required capital through investors to implement this plan.

2.11 Project Technical Objectives

2.11.1 Verify Performance of M-C Power's Latest Stack Design

The 75 kW MCFC stack which was tested under this project included several changes to components expected to improve performance (power density and efficiency) and life and reduce costs compared to the 250 kW stack tested at Miramar in 1997. The changes were prompted by information and experience gained from the 1997 test and from M-C Power's continuing research and development program. Many advances have been made since mid-1995 when the components were selected for the stack to be used at Miramar. Those advances involve changes in materials formation, manufacturing technologies, and component thickness. The gas flow pattern across the cells was changed to cross flow from counter flow to reduce pressure differentials at the seals and provide more flexibility in operation.

Each of the changes has been tested in small scale (100 cm^2 and 1000 cm^2 cells and stacks) under simulated operating conditions at the testing facilities at M-C Power or IGT. This project was necessary to verify that these improvements can be attained under field operating conditions. The 75 kW Miramar test was the first opportunity to test this stack design at full cell size and pressurized operation. The primary test goal was to operate at a current density of 110 mA/cm^2 for at least 2000 hours. A secondary goal was to operate at a current density of 160 mA/cm^2 for at least 1000 hours. Another secondary goal was for the pressure differential between the anode inlet and the cathode outlet to be less than 12 inches water gage.

2.11.2 Evaluate Anode Recycling on Performance

One of the parameters affecting fuel cell stack performance is the use of fuel on the anode side of the cell. Utilization is the percentage of fuel that is consumed as it passes across the cell. At low utilizations there is more flexibility in operation but electrical efficiency is reduced. At high utilizations, efficiency is best, but the operation becomes more sensitive to maldistribution of gas flows. If gas flows are not uniform, localized shortages of fuel can occur and damage to the cell could result.

By recycling anode exhaust gas (that is, recycling unused fuel), the system can operate at a lower utilization per pass across the cells while maintaining a high utilization overall. This arrangement should also provide a more constant gas flow rate and thus a more uniform gas flow distribution. In turn, this will provide a more uniform cell voltage distribution and longer cell life. Those improvements have to be weighed against the additional capital and operating cost incurred to incorporate anode recycle into the system. The 75 kW Miramar Test provided the operating data needed to make that evaluation. This test also showed whether or not there are impacts on the operation of the reformer or other parts of the power plant.

There are two primary reasons for conducting the anode recycle operation. One is to facilitate higher overall utilization while, at the same time, lowering the fuel utilization per pass. The other is to slightly improve the flow distribution within the anode flow channels, and thereby improve cell voltages. This is possible because the amounts of hydrogen and carbon monoxide are increased at the anode inlet for electrochemical reaction as a result of anode recycling. The recycling of high temperature anode exhaust to the reformer is accomplished by using a simple ejector with steam as the motive fluid, which requires no maintenance and is inexpensive when compared to a high temperature blower.

The anode recycle operation began at about 3638 test hours. After the anode recycle operation was fully established around 3666 test hours, the operating personnel were able to steadily increase the stack load without changing the natural gas feed rate to the reformer. Consequently the stack dc power increased from about 84 to 96 kW (i.e., at ~1425 amps of stack load) with the concurrent increase in fuel utilization. The net effect of anode recycle operation on the stack voltage can be seen between 3638 and 3666 test hours in Figure 15. The net gain for the whole stack (110 cells) was about 1.5 volt.

In theory, if the flow distribution is perfect in the stack, the anode recycle operation will reduce the stack voltage slightly because of the dilution of hydrogen concentration by recycling. The observed slight increase in stack voltage is a clear indication that the flow distribution in many cells had been improved by the anode recycle. Based on the measured flow rates and compositions, the fuel utilization per pass appeared to be at least 10 percent lower than the corresponding overall fuel utilization without anode recycle.

From this anode recycle operation, sufficient engineering data have been collected for guiding the on-going commercial designs. These data clearly demonstrate that the anode recycle operation, as implemented with a cost-effective steam ejector, did improve the stack voltage and increased the allowable overall fuel utilization for stack MCP-8 during the Miramar operation.

2.11.3 Obtain Operating Data for Future Design Work

The Miramar Power Plant is highly instrumented and incorporates a data acquisition system that monitors and records 220 operating variables (such as temperatures, pressures, gas flow rates, status and position of valves and other components) as frequently as every 30 seconds. This data was gathered during the initial startup, normal operation, anode recycle operation, and transfers from on-line operation to off-line and visa versa.

All of these data were collected for the purpose to identify the impact of each design change tested on improving the commercial viability of the MCFC Generator, including an assessment of the effect on capital cost, operating cost, stack life, system reliability, and the cost of power produced. Changes that produce a net benefit for potential users will serve as the basis for future designs. The test results will also be compared to the results predicted by M-C Power’s design model. Large discrepancies will be examined further to determine the reason, if possible. The model was updated as appropriate to make it a more accurate and reliable tool for evaluating proposed design changes in the future.

2.12 Project Economic Objectives

The overall economic / cost objectives of this project for commercial power plants were:

- The total installed cost projection in the range of $1,300 / kW to $1,500 / kW.
- The projected cost of electricity in the range of $0.05/kWh to $0.07/kWh

2.12.1 Total Installed Cost

Because this power plant was already on-site and was only modified to accept the subject 75-kW stack and both the original power plant and the stack were the first of their kind, no economic analysis was planned or performed. However, the preliminary estimates suggest that the stated economic objective (installed cost) are achievable.

2.12.2 Cost of Electricity

Because this power plant was already on-site and was only modified to accept the subject 75-kW stack and both the original power plant and the stack were the first of their kind, no cost of electricity estimates were planned or performed. However, the preliminary estimates suggest that the stated electricity cost objective can be achieved.

2.13 Commercialization Potential

The commercialization potential is high from a technical standpoint as evidenced by the progress made in the last year as discussed here. From a business perspective, commercialization requires an infusion of capital, which M-C Power needs to pursue.

Over the past decade, the regulated electric industry was successful at eliminating barriers to cogeneration and self-generation, such as supplemental, backup, and / or standby charges, modified rate structures, and project buy-outs. With full competition in the electric marketplace, some of these services will be available from competitive sources. Therefore, market forces will set the price and distributed generation can now compete on a leveled playing field. For fuel cells to achieve the promise they have always offered, developers must introduce products that are cost-effective and durable. M-C Power's Commercialization Team realizes that its product must compete with commodity priced energy supplies while providing customers added-value services. The commercialization program is focused on developing and verifying the technology that will allow the Team to introduce a cost-effective product with the durability demanded by the marketplace.

This section presents a summary of the key accomplishments achieved in the past year by the commercialization team, including recent full-area stack test results, commercial manufacturing improvements, and the BOP equipment status.

The commercialization Team has developed a strategy to move decisively through the Technology Development and Product Design and Improvement stages, including ISO9100 certification in the first quarter of 2001. Successfully fulfilling the objectives of these programs will bring MCFCs to commercialization.

Product Design and Improvement (PDI) activities began in 1995 in parallel with the final steps of the Technology Development efforts. The major focus of the Product Design and Improvement activities are to address cost reduction issues and to establish the commercial readiness of the power plant, stack technology, and marketplace infrastructure. Since the start of the PDI program, sub-scale stack and manufacturing development at the component level has led to verification of market entry and advanced technologies manufactured in a commercial manufacturing environment and tested in prototype power plant hardware as a precursor to commercial stack demonstrations.

Within the last year, M-C Power has delivered two 75-kW stack modules. The first was used for an extended process and control (PAC) test of the BOP, while the second stack was operated (as discussed previously in this report) in the fully integrated power plant at Miramar. The primary objective of this test was to evaluate a commercial cell package manufactured by M-C Power and to demonstrate improvements to the balance of plant (BOP) components, including the hot gas recycle blower and turbo-charger, as well as to test demonstration plant systems conditions and operating parameters.

The major barrier to successful commercialization has been reducing the plant and stack costs to competitive levels. Concurrently, M-C Power has an aggressive manufacturing development and engineering program in place to identify, optimize, and institute advanced component and balance of plant (BOP) technologies that provide improved plant performance and endurance characteristics while decreasing costs.

Cost reductions have been demonstrated through concurrent raw material cost reductions, elimination of manufacturing processes, increases in manufacturing rates, and weight reduction of stack and plant components. While significant cost reductions and manufacturing improvements have already been realized, the challenge remains to further reduce costs while demonstrating increased stack performance and endurance. Progress made this year toward achieving the market entry costs includes the following.

Low-cost matrices from low-cost precursor materials were developed under a Department of Energy Phase II Small Business Innovative Research project, completed at the end of 1998. Earlier versions of the lower cost matrix exhibited excessive shrinkage during conditioning. Within the past year, an alternate lower cost matrix formula was developed with different lithium and aluminum precursor materials having significantly lower weight loss and shrinkages during conditioning.

The unsintered cathode was verified to have superior performance in addition to the significant cost reductions offered through eliminating the heat treating process.

The performance of physically mixed, technical grade carbonates were verified which will reduce the raw material costs by 93 percent, from \$35.20/kg to \$2.43/kg.

The projected separator plate raw material costs were reduced by 10 percent through the identification of alternate vendors.

The projected cost of the market entry non-repeat parts decreased ~23 percent based on the specification of a cast plenum and the implementation of a thermal barrier which eliminates the need for high temperature materials.

Power densities of 133-136 W/ft^2 (current densities of 200 mA/cm^2) at 3 atmospheres with systems gases have been demonstrated at the bench scale level with significantly lower decay rates. More importantly, the low temperature (575° C) performance has been increased by 119 mV compared to early Li/Na cell packages.

Overall, M-C Power has demonstrated 90 percent of the 2002 and 90 percent of the 2005 power density targets in bench scale tests. Further, IHI has verified our technology development efforts by recently scaling up IMHEX® stack technology to 0.5 m^2 (5.4 ft^2), 14 cells, and still demonstrating 135 W/ft^2 (when corrected to MCP power plant conditions), or once again 90 percent of the 2002, market entry power density target. This same stack has demonstrated <4 mV/1000 h durability during steady state testing for 8,000 hours. Additionally, this stack produced world record power densities, 228 W/ft^2 at 300 mA/cm^2, at their test facility conditions.

Endurance improvements have been demonstrated by the implementation of a Li/Na electrolyte cell package, which offers improved resilience at higher current densities, and with humidified, pressurized, systems conditions because of its lower vapor pressure. In addition, the Li/Na electrolyte offers a higher conductivity and lower cathode solubility compared to the Li/K based electrolyte systems. A Li/Na cell package was scaled up to full-area manufacturing and assembled into our 75-kW Stack MCP-8.

Manufacturing improvements implemented within the last year have targeted increasing the existing factory capacity to 10 MW/year. Plant upgrades include installation of an automated mixing system and improved drying system that have enabled a two times increase in tape caster belt speed. M-C Power's tape casting speed now exceeds commercial targets. The manufacturing processes of the market entry stack components have been scaled up to the commercial manufacturing mode. Manufacturing process and layout simulations are underway to generate improved plant designs for the future full capacity manufacturing facility.

BOP equipment reliability is currently being demonstrated through extensive testing in the BOP Test Facility. Within the last year, Elliot turbogenerator modules completed the short term testing phase of 500 hours of continuous operation. Other BOP Test Facility milestones include: evaluating different hot gas recycle blower seal designs and immediately implementing a low cost candidate at the Miramar Power Plant and verifying the endurance of a low cost Heat Recovery Steam Generator (HRSG).

Demonstration plant designs have been completed for high efficiency by implementing the following design improvements: thermal integration, increased power densities, and co-generation. In addition, the demonstration BOP operations have been simplified by minimizing controls, implementing proven operating procedures, simplifying the startup/shutdown operations, and integrating functions.

2.14 Benefits to California if Technology is Commercialized

There are many potential benefits to the electricity consumers and the general population in California from the Project. Some of the benefits are short term and some are long term. The primary benefits are environmental and health related, but there are also productivity and other economic benefits.

The short term benefits are those from the execution of this project itself. As described in detail elsewhere, this project involved assembling, installing, and conducting operational tests of an advanced 75-kW MCFC stack at Miramar. The project duration was 18 months and pretest and test activities took place at the Miramar site for 11 months.

Site work was overseen by personnel from SDG&E. Skilled operators were hired locally to operate the test facility. Local subcontractors and suppliers were used to provide installation, repair, and maintenance services and materials and spare parts for the project. Plant installation, start-up and operation-assistance was provided by Bechtel Corporation, San

Francisco. M-C Power personnel responsible for data collection and analysis, test direction, and problem resolution were essentially residing in California near the test site for most of the test schedule. M-C Power also used the services of a local consultant, AESC in Carlsbad, to help manage the project and maintain close communication with the Commission so all parties were kept well informed and problems were addressed promptly. In all, M-C Power estimates that $1,400,000 was spent in California. That amount is 46 percent of the total project cost and exceeds the amount of funds provided by Commission for the Project. Besides these local benefits, many other kinds of benefits are discussed in the following sections.

2.14.1 Energy Savings

Higher efficiency means less energy or fuel consumption to generate a unit of electricity. A 50-80 percent efficiency improvement over existing or conventional power plant efficiency provides substantial energy savings. The power produced by the MCFC test unit displaced power from a central power station in the amount of 260 MW-hrs. Emissions of NO_x, CO, and hydrocarbons from the MCFC stack will be at least 90 percent less. Using waste heat to generate steam for use in Miramar's district heating system also saved a small amount of fuel.

2.14.2 Energy Cost Savings

MCFC Generators are also expected to improve the productivity of users and lower their costs due to improvement in power quality and reliability. More and more business operations are dependent on computers and electronic controls which are sensitive to the quality of the power received. Poor quality power (voltage sags and surges, current fluctuations, etc.) can cause shutdowns or misoperation, which results in lost production and additional costs to return operations to normal. In most cases, these costs far exceed the cost of the power used. Power quality is high from an MCFC Generator because a power conditioner is an integral part of the system. In addition, having the MCFC Generator located at the point of use avoids the power quality problems created within the transmission and distribution system itself including those fed back into the system by customer operations. The on-site location of the MCFC Generator also helps avoid lost power due to storms, earthquakes, accidents and other phenomena that knock out transmission and distribution lines and transformers. The MCFC Generator itself is expected to be more reliable than conventional generators because there are few moving parts and the operation is different.

It is difficult to quantify the economic impact of all of the above on the State of California. Clearly, the MCFC Generator will be able to help resolve some health impacts and difficult environmental problems that have extensive direct and hidden costs. In addition, the productivity increases and cost reductions arising from having high quality, reliable power supply are realized. In addition, the use of MCFC Generators in distributed generation applications will help avoid expenditures on upgrading electricity distribution facilities and distribution line energy losses. At the same time, the cost of electricity produced by the MCFC Generator is projected to be competitive with other sources of power depending on the user's situation. Commission's levelized cost model projects a wide range of electricity prices, 5.5 to 20.9¢/kWh, depending on ownership and other assumptions (1996 Energy Technology Status Report). With commercial customers paying an average rate of about 10¢/kWh (Commission

Publication P300-95-020), it is evident that MCFC Generators can be competitive on the basis of cost alone. The other benefits also give MCFCs a decided edge.

2.14.3 Increased Employment

Based on M-C Power's forecast of sales revenue and a job creation factor of one job for each $400,000 of sales, successful commercialization of the M-C Power MCFC generator has the potential to create 2,475 jobs in the U.S. by 2008. These will be primarily manufacturing, assembly, and testing jobs. Jobs created will be for skilled and professional labor. Less than one percent of the jobs would involve unskilled field construction and maintenance personnel.

At this time, it is difficult to quantify the number of jobs that might be located in California because specific vendors and equipment suppliers have not been identified. However, California, being a larger electricity use state, would use substantial distributed power generation plants, thus generating economic growth and jobs in local economies and providing benefits locally.

2.14.4 Environmental Benefits

The long term benefits are those that occur when the MCFC technology is commercialized, with this Project being an important step in reaching that stage. The expected benefits are high efficiency, low emissions, low CO_2 production, high quality power, and high reliability. Due to concerns about global climate change, it appears that low CO_2 production will become the most important attribute of the MCFC Generator.

Those concerns about global climate change have grown to the point that the world's industrialized countries have committed to emission reductions of CO_2 and certain other gases at a United Nations conference in Kyoto, Japan in December 1997. In general, the target is, at a minimum, for the amount of CO_2 emitted in 2008 to 2012 to be at 95 percent of the amount emitted in 1990. Extrapolating from data published by the Commission on California Carbon Emission from Electricity Generation, 1994-2003, it appears 1990 emissions were the equivalent of about 92,000,000 tons of CO_2. Ninety-five percent of that amount is 87,000,000 tons. The Commission forecast is for emissions to rise to 134,000,000 tons per year by 2012. To meet the Kyoto goals, CO_2 emissions have to be reduced 47,000,000 per year by 2012. Assuming 2000 as the starting year, a reduction of 3.5 percent per year is needed.

Low CO_2 production is a natural consequence of the high efficiency of the MCFC technology in converting fuel to electricity. Using less fuel per kilowatt hour of power produced means less carbon fed to the generator and thus less carbon dioxide produced and discharged to the atmosphere. At the expected efficiency of 54 percent, the MCFC Generator will be 50 percent to 80 percent more efficient than comparably sized gas engines and turbines and many central power stations. In turn, CO_2 production from the MCFC generator (0.4 ton / MWh) will be 35 percent to 45 percent less. That is, a 1 MW unit at 100 percent load will drop the amount of CO_2 discharged to the atmosphere by 1200 to 1500 tons per year.

The alternative to using naturally low producers of CO_2 like MCFCs, is to remove CO_2 from exhaust gases. There are methods for doing that, but the problem is what to do with the gathered CO_2 to keep it from reaching the atmosphere. The options, such as underground injection or forming solid compounds, all have drawbacks and increase the cost of power production. Renewable technologies such as solar and wind power have the advantage of producing no CO_2 emissions. Unfortunately, the resource is only available intermittently, and the cost of electricity is relatively high at present. Thus, when MCFC Generators become commercial in 2002, they are expected to be an important tool for meeting the climate change goals for CO_2 emissions in California.

The MCFC technology also provides other environmental benefits — very low to essentially zero emissions of NO_x, CO, and unburned hydrocarbon, all of which contribute to the production of ozone and smog. While air quality has greatly improved, it is still a concern in several areas of California. With such low emissions, MCFC Generators can be used to replace older power units to improve air quality and allow expansion at the same time. Compared to a combustion unit emitting just 10 ppm NO_x, the MCFC Generator would lower NO_x emissions about 1 ton / MW yr.

2.15 Major Accomplishments

The Miramar power plant was successfully modified from 250-kW capacity to 75-kW capacity.

A 75-kW stack was assembled, conditioned, and acceptance tested at M-C Power's factory in Burr Ridge, IL.

The Miramar power plant was operated with the 75-kW MCFC stack for more than 3800 hours and generated 260 MWhrs of electricity at NO_x emissions under 0.5 ppm.

A Production Readiness Plan was prepared which quantifies M-C Power's current and projected production capacity.

3.0 Conclusions and Recommendations

3.1 Conclusions

The project discussed herein was to verify improvements and modifications made to the pressurized, integrated molten carbonate fuel cell (MCFC) power plant located at the Marine Corps Air Station (Miramar), Miramar, San Diego, California and to assemble, condition, and operate a 75-kW MCFC stack for performance verification. The power plant modifications were verified by a hot test of the system. The power plant was successfully operated for more than 3,800 hours on load and generated 260 MW-hrs.

M-C Power coordinated all of the planned plant modifications to accommodate the operation of a 75-kW MCFC stack at the Miramar facility. The following list shows all of the modifications completed.

Description of Modification

- New liquid nitrogen valve
- Improved turbocharger
- Permanent oil / water separator for turbocharger
- New air compressor as a backup for the turbocharger
- Improved cathode recycle blower
- Improved sulfur GC analyzer
- Improved cathode heater control panel
- New cathode bypass loop and valve
- New seal pot level switches
- New check valves
- New anode recycle loop
- New heat tracing for GC sample lines
- New trim for natural gas valve
- New boiler feed water pump as a spare
- New load bank as backup to inverter
- Modified inverter

The power plant and stack operated and produced power as follows:

Test Hours:	3828.75 hrs. (hours since stack heat-up initiated)
On-Load Oper. Hours:	3354.50 hrs. (actual hours with load applied)
Total Power Produced:	260.13 MW-hours
Nox emissions:	<0.5 ppm

3.2 Recommendations

The stack and power plant should be restarted for enhanced power output at higher current density when additional financing is secured. This will allow continued operation to establish durability and verify the ability of the power plant to withstand thermal cycles and higher current density.

4.0 Glossary

AESC	Alternative Energy Systems Consulting, Inc.
ATF	Acceptance test facility
BOP	Balance of Plant (all the equipment, controls, etc. that comprise the MCFC power generation system except for the fuel cell stack.)
CO	Carbon Monoxide
CO_2	Carbon Dioxide
Commission	California Energy Commission
EPRI	Electric Power Research Institute
GRI	Gas Research Institute
IGT	Institute of Gas Technology
IMHEX®	Internally Manifolded Heat Exchange
Li/Na	Lithium / Sodium
MCAS Miramar	Marine Corps Air Station Miramar in San Diego, CA (until recently a Naval Air Station or NAS Miramar)
MCFC	Molten Carbonate Fuel Cell
NO_x	Nitrogen Oxides
PAC	Process and control test
PDI	Product design and improvement
PIER	Public Interest Energy Research
Project	75 kW MCFC Stack Verification Test at MCAS Miramar
Psi	Pounds per square inch
S&S	Stewart & Stevenson Services, Inc.
SDG&E	San Diego Gas & Electric Company
U.S. DOE	United States Department of Energy
VDC	Volt Direct Current

Appendix I

Emissions Test Report
M-C Power Fuel Cell Facility
Marine Corps Air Station, Miramar CA

November 3, 1999

Appendix II

Production Readiness Plan

Appendix I

Emissions Test Report
M-C Power Fuel Cell Facility
Marine Corps Air Station, Miramar CA
November 3, 1999

Prepared for

M-C Power Corporation
Burr Ridge, Illinois

Prepared by

Greg W. Stevens

Alternative Energy Systems Consulting, Inc.
Carlsbad, California

Introduction

Under subcontract to Alternative Energy Systems Consulting Inc. (AESC), Fossil Energy Research Corporation (FERCo) completed the second operational emissions test of the M-C Power Molten Carbonate Fuel Cell (MCFC) power plant at MCAS Miramar on November 3, 1999. This testing was required to assess the emission levels of criteria pollutants while the MCFC power plant was operating.

The tests included flue gas measurements of NO_x, SO_2, volatile hydrocarbons, CO, Methane, CO_2 and O_2 at the fuel cell's cathode exhaust sampling port and NO_x, CO, volatile hydrocarbons and Methane in the ambient air. SO_2 samples were also collected at the BOP exhaust stack, which are to replace the samples that were inadvertently contaminated during the last operational test. FERCo's detailed findings are contained in their report following this summary.

Sampling Location and Test Conditions

The MCFC power plant is located at the Marine Corps Air Station in Miramar, CA. The fuel cell is sited 50 yards to the northwest of a roadway intersection and approximately 1 mile from the air station runway. FERCo collected emission samples from the inlet side of the turbine section of the turbocharger.

FERCo noted and logged ambient conditions and vehicular activity during the tests.

- Temperature: 68 to 85°F, relative humidity 25 to 52%.
- Bright Sunshine.
- Calm to mild wind from the west.
- Moderate vehicular traffic on adjacent roadways.
- Periodic activity on air station runway.

MCFC Operating Conditions

The air emissions tests were conducted while the MCFC plant was operating at full capacity (76.8 kW DC). There are several input gases that are critical for proper operation of the fuel cell plant: Nitrogen (N_2) gas is injected into the system to regulate mass flow and provide a seal for the cathode blower; Carbon Dioxide (CO_2) is introduced into the system to enhance the anode electrochemical reaction; and natural gas is utilized in the reforming process. Average flowrates of these critical inlet gases during emissions testing are contained in Table 1.

Plant operators have stated that the stack was operating normally during the emission test period.

Table 1. – Average Inlet Gas and Water Flow Rates of the MCFC plant (at Full Capacity).

Gases/Effluents	Flow Rate
CO_2	23.5 scfm
N_2	20.7 scfm
Natural Gas	
Pre-heated NG to reformer	33.3 lb/hr
HRSG burner fuel	21.5 lb/hr
Make-Up H_2O	0.25 gal/min
Plant air-intake	388 scfm @ 28.7 psig

Summary of Results and Discussion

The results of the second operational emissions test for the MCFC at MCAS Miramar are summarized in Table 2.

Table 2. –Operational Emissions Test Summary for MCFC at MCAS Miramar, November 3, 1999.

	NO_x	CO	NMHC	Methane	SO_2
Cathode Exhaust					
ppm (15% O_2)	0.4	176	2.8	149	ND
lb/MMBtu	0.001	0.22	0.002	-	ND
lb/hr	0.001	0.41	0.0038	-	ND
Flue gas conditions					
Temp, F	1207				
O_2, %	11.8				
CO_2, %	9.7				
Flow, dscfm (68 F)	351				
Ambient Air					
ppm	0.0	0.3	1.9	2.6	ND
Adjusted Emission Levels					
ppm	0.4	175.7	0.9	146.4	-

ND = Not detectable – For both Cathode Exhaust and Ambient Air Measurements.

Baseline air emissions results established that there were no abnormally high pollutant levels in the ambient air surrounding the plant at the time of the second operational test. Adjusted operational emission levels of CO, NHMC and Methane based on measured ambient pollutant levels are 175.7, 0.9 and 146.4 ppm, respectively.

SO_2 samples were collected at the BOP exhaust stack and cathode exhaust sampling port. Emission levels at each of the monitoring points were below detection limits (< 0.2 ppm).

Emissions Standards

Emission standards for stationary gaseous-fueled internal combustion engines operated in the San Diego County Air Pollution Control District (SDCAPCD) and South Coast Air Quality Management District (SCAQMD) are shown for comparison in Table 3. Also included in Table 3 are typical emission levels for a natural gas fueled combined cycled unit.

Table 3. –SDCAPCD and SCAQMD Standards and Internal Combustion Engine Emissions Summary.

Engine Type	NO_x	CO	NMHC	SO_2	CO_2
Emission Standards(ppm):					
Gas turbine (≥0.3 & < 2.9 MW)[1]	42	-	-	-	-
Reciprocating I/C (>50 bhp)[2]:					-
-Rich-burn engine	50	-	-	-	-
-Lean-burn engine	125	-	-	-	-
Stationary I/C engine (>50 bhp)[3]	36	2000	250	-	-
Emission Levels (lb/MMBtu):					
Natural Gas Combined Cycle Unit[4]	0.042	-	-	0	110

1. SDCAPCD Rule 69.3.1 – STATIONARY GAS TURBINES – BRCT.
2. SDCAPCD Rule 69.4 – STATIONARY RECIPROCATING INTERNAL COMBUSTION ENGINES.
3. SCAQMD Rule 1110.2 – EMISSIONS FROM GASEOUS AND LIQUID-FUELED ENGINES.
4. The Cogeneration Journal – Vol. 6, No.3 1991.

It should be noted that the SDCAPCD is in attainment for CO and there is no standard established for stationary natural gas fired I/C engines at this time.

TEST REPORT

FUEL CELL AND HRSG EMISSION TESTS
MC POWER FUEL CELL TEST SITE
MIRAMAR MARINE CORPS AIR STATION
NOVEMBER 3, 1999

Prepared for

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Laguna Hills, California
December 1999

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INTRODUCTION AND SUMMARY OF RESULTS

Fossil Energy Research Corporation (FERCo) was retained by Alternative Energy Systems Consulting (AESC) to conduct a series of air emissions tests on a 75 kW fuel cell installed at MC Power's fuel cell test facility at Miramar Marine Corps Air Station (Miramar). The program includes three tests: (1) background ambient air tests prior to fuel cell start up on June 11, 1999, (2) emission tests approximately three months after start up on August 30, 1999, and (3) emission tests approximately five months after start up on November 3, 1999.

This document is the test report for the November 3 emission tests. The tests included measurement of NO_x, CO, SO_2 and volatile hydrocarbons in the cathode exhaust gases, SO_2 in the stack on the roof of the balance of plant building, and NO_x, CO, and volatile hydrocarbons in the ambient air.

Included in this document are a description of the sample locations (Section 2), the test methods (Section 3), and the test results (Section 4). Supplemental information including QA and calibration information, test method details, and raw data sheets are included in the Appendices.

FERCo's Project Manager and on-site field team leader for these tests was Mark McDannel. He was assisted by Lawrence Pedregon of Delta Air Quality Services. Delta served as a subcontractor to FERCo, and provided the test equipment. Mr. Greg Stevens coordinated the tests for AESC.

The results of the tests are presented in Table 1. Pollutant concentrations, corrected for dilution to 15% O_2, were 0.4 ppm for NO_x, 176 ppm for CO, and 2.8 ppm for volatile nonmethane hydrocarbons. Ambient air levels were 0.0 ppm for NO_x, 0.3 ppm for CO, and 1.9 ppm for volatile nonmethane hydrocarbons. SO_2 levels were not detected at the cathode exhaust and at the balance of plant exhaust.

Table 1. Emissions Test Summary, MC Power Fuel Cell, November 3, 1999

Cathode Exhaust Tests	**Test 5**	**Test 6**	***Average***
Gas conditions			
Temp, F	1207	1207	1207
O_2, %	11.91	11.75	11.8
CO_2, %	9.73	9.64	9.7
Flow, dscfm (68 F)	351	351	351
NOx			
ppm	0.6	0.5	0.6
ppmc (15% O_2)	0.4	0.3	0.4
lb/MMBtu	0.001	0.001	0.001
lb/hr	0.002	0.001	0.001
CO			
ppm	269	270	270
ppmc (15% O_2)	177	174	176
lb/MMBtu	0.22	0.21	0.22
lb/hr	0.41	0.41	0.41
Volatile Nonmethane Hydrocarbons, reported as CH_4			
ppm	3.2	5.5	4.4
ppmc (15% O_2)	2.1	3.6	2.8
lb/MMBtu	0.0015	0.0025	0.0020
lb/hr	0.0028	0.0048	0.0038
*Methane, ppm**	149	149	149
SO_2			
ppm	ND<0.2	ND<0.2	ND<0.2
ppmc (15% O_2)	ND<0.1	ND<0.1	ND<0.1
lb/MMBtu	ND<0.0004	ND<0.0004	ND<0.0004
lb/hr	ND<0.0007	ND<0.0007	ND<0.0007
Balance of Plant Exhaust Tests	**Test 7**	**Test 8**	***Average***
SO_2			
ppm	ND<0.2	ND<0.2	ND<0.2
Ambient Air Tests	**Test 9**	**Test 10**	***Average***
NOx, ppm	0.0	0.0	0.0
CO, ppm	0.3	0.3	0.3
Volatile Nonmethane Hydrocarbons, as CH_4	1.9	1.9	1.9
Methane	2.7	2.6	2.6

2

SAMPLE LOCATION AND AMBIENT CONDITIONS

Samples were collected at three locations: the cathode exhaust, the balance of plant exhaust, and the ambient air.

Cathode Exhaust. Cathode exhaust samples were taken from a tee fitting off of the existing cathode exhaust sample line to the plant gas chromatograph. For testing the sample line was connected to a fitting downstream of a three-way valve, and the valve was opened to collect the samples.

*Balance of Plant Exhaust s*amples were collected from the exhaust stack on the roof of the balance of the plant equipment building. The roof is approximately 15 feet above the ground.

A drawing of the stack and sample locations is included in Appendix C. The stack is circular, 12" in diameter, and extends 14-16 feet above the roof line. There are no conventional gas sampling ports installed on this stack. SO_2 samples were drawn from a stainless steel probe inserted approximately two feet in from the stack exit.

Ambient Air. The plant is located within 50 yards of an intersection of two roadways and approximately 1 mile from the air station runways. The roads are to the west and north of the building, and the runway is to the southwest. Samples were taken approximately 4 feet above ground level near the cathode exhaust sample port.

Area weather and vehicular activity were noted during the tests, and the log is included in the Appendices. Key conditions in the area (temperatures recorded in the shade) were:

1. Temperature: 68 to 85°F, relative humidity 25 to 52%.
2. Bright sunshine.
3. Calm to mild wind from the west.
4. Moderate vehicular traffic on the adjacent roadways.

5. Periodic aircraft activity on the runway. Jet exhaust was not smelled.

3

TEST METHODS

This section presents the test methods used. Copies of FERCo's CARB Certification are included in Appendix A; Appendix B presents quality assurance and calibration activities that were followed for the tests. The tests were performed in accordance with the proposal submitted by FERCo to AESC dated May 21, 1999.

The test methods used are summarized in Table 2. The subsections below present additional discussion.

Table 2. Test Methods

Parameter	*Reference Method*	*Measurement Principle*	*Instrument Range (continuous methods)*	*Quantitation Limit*
NOx	EPA 7E	Chemiluminescent	0-10 ppm	0.2 ppm
CO	EPA 10	Infrared	0-200 ppm	1 ppm
CO_2	EPA 3A	Nondispersive infrared	0-20 %	0.2%
O_2	EPA 3A	Electrochemical cell	0-25%	0.2%
THC	EPA 25	GC, collect in summa canister		0.1 ppm
SO_x	EPA 8	Acid-base titration		0.2 ppm
Weather		T/RH meter, observation		
Area Activity		Observation		

3.1 *NO_x, CO, O_2 and CO_2 Measurement*

This section presents a detailed description of the measurement system, system performance checks and calibrations, and test methods. Testing was in accordance with EPA Methods 7E, 10, and 3A.

Gaseous emissions species of NO_x, CO, and CO_2 were measured using an extractive continuous emissions monitoring (CEM) package contained in a mobile emissions laboratory. A schematic of the sample handling system is presented in Figure 1. The system is comprised of three basic subsystems, including: (1) sample acquisition and conditioning system, (2) calibration gas system, and (3) analyzers. Each of these subsystems is described in the following paragraphs.

The sample acquisition and conditioning system contains components to extract a representative gas sample, transport the sample to the analyzers, and remove moisture and particulate material from the sample. In addition to performing these tasks, the system must preserve the measured species and deliver them intact for analysis. For this testing, a single sample line was connected to a condenser, hotline and probe at the stack. The sampling system used for this testing is shown schematically in Figure 2.

The stainless steel sample probe was connected to a condenser located on the stack sample platform with a heated Teflon sample line. This heated line was maintained at a temperature of nominally 230°F to prevent condensation. The stack mounted condenser was maintained at 36°F. The condenser/pump arrangement at the stack included one pass through the condenser under vacuum and one pass through the second chamber of the condenser under pressure. Excess sample is vented in the truck through a back-pressure regulator, maintaining a constant pressure of 5-6 psig to the analyzers.

The calibration system is comprised of two parts: the analyzer calibration, and the system bias check (dynamic calibration). The analyzer calibration equipment includes pressurized cylinders of certified span gas, and a standard gas divider to obtain desired calibration levels. The gases used for this program will be certified to ±1% by the manufacturer to comply with reference method requirements. The cylinders are equipped with pressure regulators which supply the calibration gas to the analyzers at the same pressure and flow rate as the sample. Selection of zero, span, or sample gas directed to each analyzer is accomplished by operation of the sample/calibration selector valves.

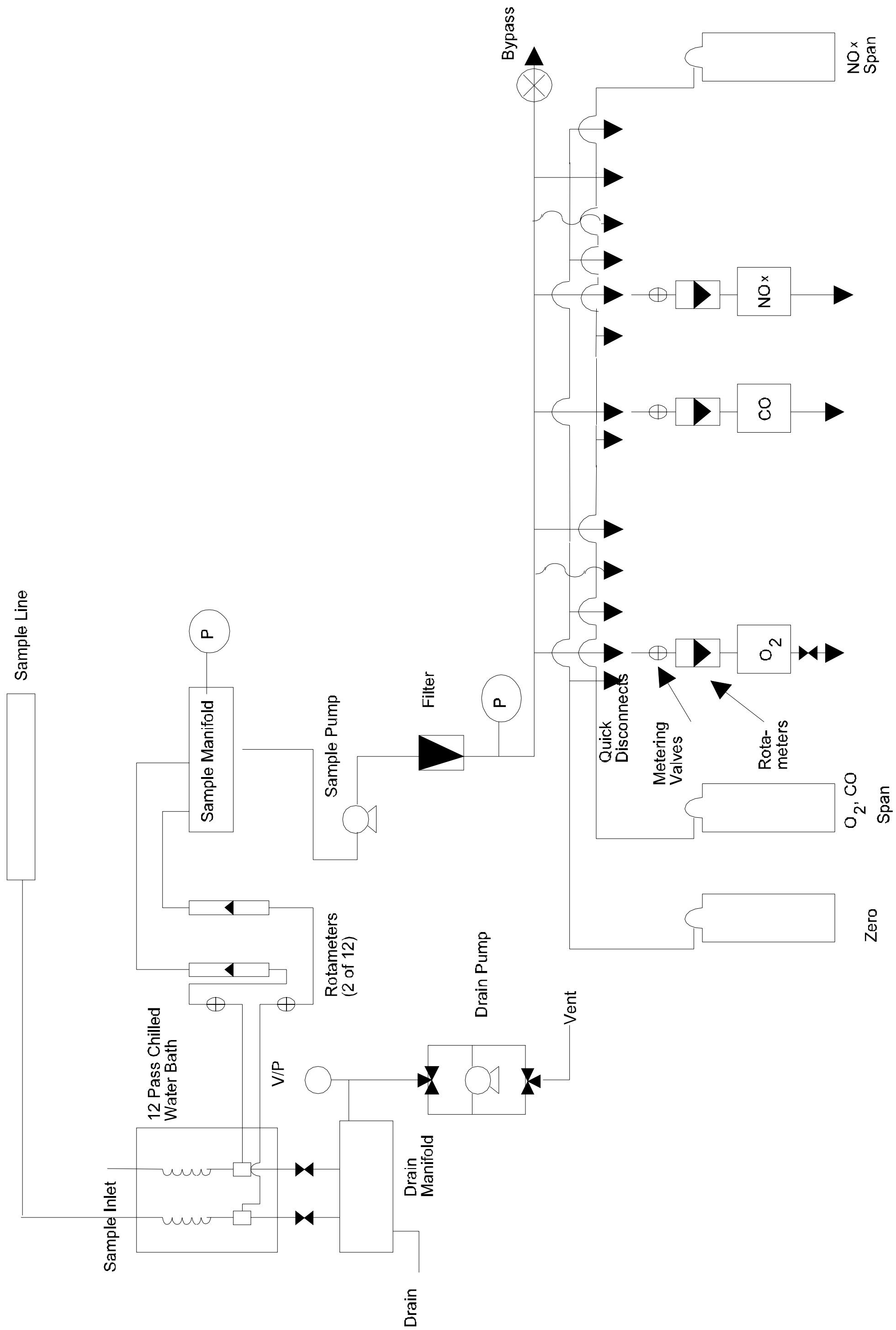

Figure 1. Sample Handling System

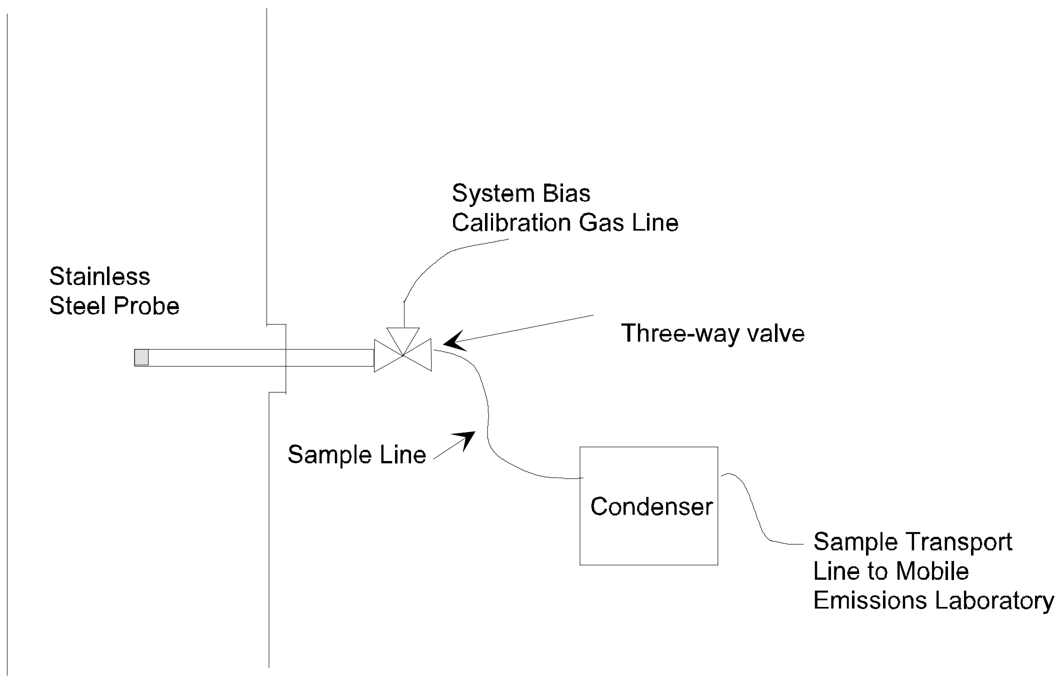

Figure 2. Gaseous Emissions Sample System Schematic

The system bias check is accomplished by transporting the same gases used to zero and span the analyzers to the sample conditioner inlet (probe exit). The span gas is exposed to the same elements as the sample and the system response is documented. The analyzer indications for the system bias check must agree within 5% of the analyzer calibration. Values are adjusted and changes/repairs are made to the system to compensate for any difference in analyzer readings.

Gaseous emissions data was recorded continuously during the test period on a multichannel, 10-inch Yokogawa strip chart recorders/data logger. The strip charts are included in the Appendices and are annotated to identify dates, times, recorder speed, calibration gas values, analyzer calibrations, system bias tests, and individual sample point locations during each test period. The averaged strip chart readings were corrected for drift using the averages of the pre- and post-test zero and span calibrations. The average zero and span calibrations are determined using Equations 3-1 and 3-2, respectively.

$$Z_a = \frac{(Z_f - Z_i)}{2} + Z_i \qquad \text{(Eq. 3-1)}$$

$$S_a = \frac{(S_f - S_i)}{2} + S_i \qquad \text{(Eq. 3-2)}$$

Z_a, S_a = average zero or span strip chart divisions
Z_f, S_f = final zero or span strip chart divisions
Z_i, S_i = initial zero or span strip chart divisions

Equation 3-3 is then used to determine the corrected gas concentrations

$$C_m = (D_m - Z_a) \_ \frac{(C_s)}{(S_a - Z_a)} \qquad \text{(Eq. 3-3)}$$

C_m = drift corrected gas concentration
D_m = measured division for sample gas on strip chart
C_s = span gas concentration

Measured gas concentrations were also corrected to 3% using Equation 3-4:

$$C_{3\%O_2} = C_m - \frac{(20.9 - 3.0)}{(20.9 - C_{mO_2})} \qquad \text{(Eq. 3-4)}$$

$C_{3\%O2}$ = gas concentration corrected to O_2

C_{mO2} = drift correct O_2 concentration

3.2 *SO_x Measurement*

Two samples were collected at the cathode exhaust and two samples were collected at the balance of plant exhaust for SO_2 using EPA Method 8. The method was modified by elimination of the isopropanol impinger designed to separate SO_3 from SO_2. Total SO_x was collected in two impingers containing 3% H_2O_2. Analysis was by acid-base titration.

3.3 *Hydrocarbon Measurement*

Volatile hydrocarbons were measured according to EPA Method 25. Samples were collected in evacuated Summa canisters, and analyzed by gas chromatography for methane and total nonmethane volatile organics. Analyses were performed by Atmospheric Assessment Associates in Calabasas, California.

3.4 *Exhaust Gas Flow Measurement*

At the cathode exhaust, gas flow measurements were obtained from plant instrumentation.

At the balance of plant stack, exhaust gas flow was calculated based on a system mass balance. Inputs to the mass balance calculations were the fuel input to the fuel cell, the fuel input to the supplemental burner, and exhaust O_2 and CO_2 concentrations. The calculations are presented in Appendix D.

4

RESULTS

The results of the tests were presented in Table 1. Results are presented as-measured (ppm by volume on a dry basis), as ppmc corrected for dilution to 15% O_2 (the dilution standard commonly used for reporting emissions from internal combustion sources), as emission factors (lb/MMBtu), and as mass emission rates (lb/hr). NO_x was measured at 0.4 ppmc, CO at 176 ppmc, and volatile nonmethane hydrocarbons at 2.8 ppmc. SO_2 was not detected at 0.1 ppmc. The NO_x level is subject to a high relative uncertainty because it is so low. Uncertainty is estimated at 2% of scale, or 0.2 ppm.

There were no sampling problems that impacted the results. The one deviation to the reference methods was that the calibration error specification of +/- 2% was not met for the mid-scale NO_x gas. The Calibration Error check involves measuring as-found instrument response to a zero gas and two calibration gases. This discrepancy is not considered to have a significant impact on the results, particularly since actual concentrations were so close to zero and zero gas Calibration Error and System Bias checks on the NO_x analyzer were within specifications.

Appendix II

PRODUCTION READINESS PLAN

M-C Power Corporation
8040 South Madison Street
Burr Ridge, IL 60521

February 18, 2000

PRODUCTION READINESS PLAN
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PRODUCTION READINESS PLAN

1. SUMMARY

M-C Power's fuel cell stacks are produced at our manufacturing facility in Burr Ridge, IL. This facility can support a production capacity of 10 MW per year. The identification of critical production processes, equipment, and facilities is described in Section 4.

M-C Power's efforts to reduce the MCFC cost are a continuous activity. These activities are translated into current cost reduction efforts such as: (1) Identifying and qualifying alternative low cost raw materials; (2) Eliminating the sintering process for cathode electrodes; (3) Eliminating casting solvent materials; (4) Increase production capacities in mixing, tape casting , sintering and cutting operations; (4) Identifying and eliminating sources of variation or special causes affecting processes; (5) Increasing repeatability and reproducibility. These achievements motivate us to achieve another level on the continuous cost reduction plan which are: (1) Develop a lower cost matrix formulation, (2) Eliminate solvent based formulations so carbon beds will be not utilized, (3) Increase manufacturing rates and yields, (4) Reduce separator plates and Non Repeat Part costs and (5) Increase Power Density. A more detailed description of these items is shown in Section 5.

The projected M-C Power manufacturing costs have been presented to the US Department of Energy. These costs include advanced low cost components and plant production capacity starting at 15 MW for the year 2002 increasing through the year 2008. A basic assumption is that the performance and endurance goals are met by that year. The performance and endurance are the primary objectives compared to either the raw material costs or labor, as this determines the number of cells per stack. This document also provides a description of the cost model that is shown in Section 6.

2. INTRODUCTION

In 1989, the Institute of Gas Technology (IGT) transferred their IMHEX ® technology to M-C Power. Since that time, M-C Power has advanced the IMHEX ® MCFC design concept from laboratory experiments to proof-of-concept field-testing. Our field testing demonstrations include commercial-scale hardware and components developed specifically for the IMHEX ® design concept. IMHEX ® stands for "Internally Manifolded Heat Exchanger". It describes a dependable, simple method for moving gas through a stack of flat cells to fuel the reaction that produces electricity. The manifolds that perform this function are simply ducts created as individual cells and placed on top of one another. Designing the manifolds into the cell stack avoids complications that can arise if the manifold system is designed for attachment to the stack's external surfaces; a method often found in other fuel cell designs.

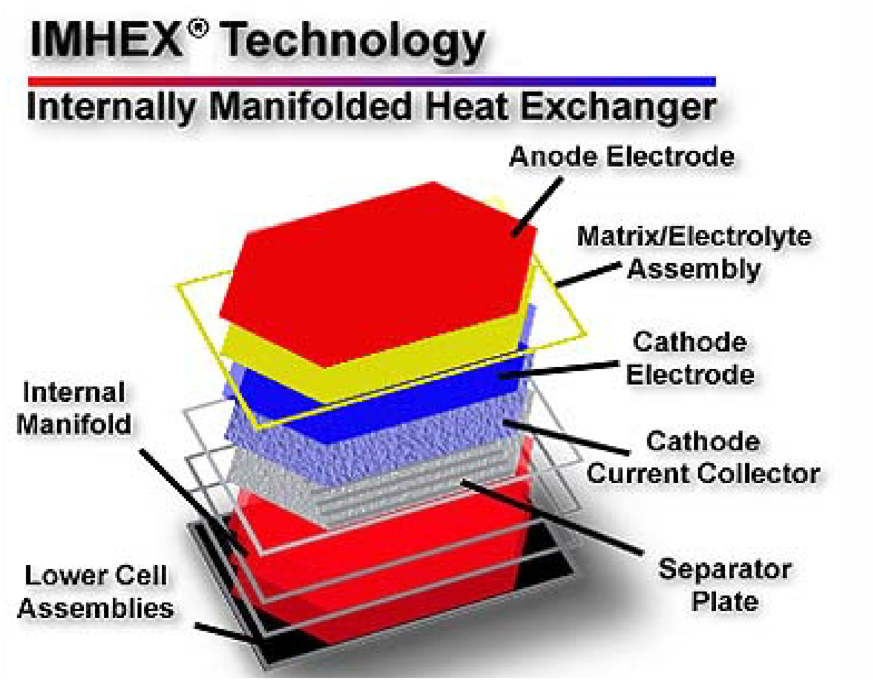
Molten Carbonate Fuel Cells (MCFC) are the most efficient of the fuel cell technologies for power generation. Power plants based on MCFC's are not only efficient they also:

- Achieve low emissions of NO and CO2
- Produce premium quality power

- Co-generate steam or hot water
- Are suitable for distributed generation

A number of development and full-scale field tests have been done or are currently underway to finalize the design and performance specifications of the molten carbonate fuel cell -MCFC- (Figure 1). There are some areas in which new technologies need to be developed or refined in order to reach the market entry goals for the IMHEX Molten Carbonate Fuel Cell Power Plant (IMHEX-MCFC Power Plant). These areas, whose improvements are ongoing, concentrate on plate and Non-Repeat components. It is estimated that about 50% of a projected stack cost are due these two components.

Figure 1: IMHEX MCFC



3. OBJECTIVE

The objectives of this Commercial Manufacturing Readiness Plant are:

a) Define production processes for manufacturing of a commercial IMHEX Molten Carbonate Stack.
b) Identify requirements of machines, equipment, manpower, methods, materials, and facilities for manufacturing of a commercial IMHEX Molten Carbonate Stack.
c) Determine capacity constraints imposed by the market for the current design of a commercial IMHEX Molten Carbonate stack.
d) Identify hazardous or non-recyclable materials.
e) Establish a projected cost of a commercial IMHEX Molten Carbonate Stack.
f) Establish an implementation plan to fully commercialize the IMHEX Molten Carbonate Stack.

4. STACK MANUFACTURING TECHNIQUES

4.1 Approach Overview

Fed by on-going manufacturing engineering efforts, M-C Power constantly evaluates existing and future manufacturing processes and technologies and determines ways to reduce the cost of the system and to improve the performance, producibility, and quality of the system. Much of this effort involves optimizing current manufacturing processes. As a tool for these process improvements, MC Power has developed a comprehensive manufacturing process descriptions. These descriptions include all of the process specifications, process flow charts, component recipes, production equipment, requirements and procedures needed to produce a molten carbonate fuel cell (MCFC). The process descriptions in combination with work measurement studies, will lead to identifying manpower, machines, methods, materials, and facilities where the process can be improved. Factor/Aim, a discrete simulation software, is being used to model the current process, and our future factory. This model enables us to improve our productivity, to determine the schedule to manufacture a stack, as well as developing a future Activity Based Costing Technique.

In addition to manufacturing process improvement, M-C Power is developing the procedures and tracking for the manufacturing process. We believe to improve the production yield, we must administrate the process data. The process raw data is currently used to initialize some statistical studies to bring the manufacturing process into statistical process control.

4.2 Developing a Manufacturing Plan

4.2.1 Goals and Objective

The principal goal is to produce a plan that will satisfy both functional and physical requirements at a cost that is compatible to the user. Thus the design must be producible at a cost that will permit the product to be introduced in the marketplace. In order to achieve the principal goal, the following objectives are established.

a) To maximize simplicity of design.
b) To maximize the use of economical materials that will satisfy the functional design requirements.
c) To maximize the use of economical manufacturing tooling, methods and procedures.
d) To maximize the standardization of material and components.
e) To maximize the simplicity of stack-cell assembly.
f) To maximize the simplicity of inspecting and testing the product.
g) To minimize critical process variation.
h) To minimize the generation of scrap and waste.
i) To minimize the use of non-environment friendly materials.
j) To minimize non-added value costs.

The manufacturing plan identifies the approach for duplicating a product configuration in a cost-effective manner. It is based on the results of detailed planning and analysis activities that have been conducted in the past to define the optimum approach for manufacturing of the MCFC's. All actions that are required to produce, test and deliver acceptable MCFC stack system on schedule and at minimum cost are defined in the manufacturing plan. Hence, the manpower, methods, materials, machines, time in process, and plant facilities are described and integrated into a complete sequence and schedule of events.

The manufacturing planning activities that will be accomplished are:

a) Identify production processes to manufacture an IMHEX MCFC.
b) Estimate manufacturing resources required to achieve the production goal. This means to identify requirement of manpower, machines, methods, materials, and facilities for manufacturing of a commercial IMHEX Molten Carbonate Fuel Cell.
c) Schedule definition.
d) Make or buy decisions.

4.2.2 Critical Production Processes to Manufacture an IMHEX MCFC

In many cases, the engineering design activities that are necessary for product development are often treated as a discrete functional activity, with little or no involvement of the other plant functions (e.g. manufacturing or production engineering). This approach to product development stresses performance and gives little attention to productivity considerations. As a result, the product's design meets performance specifications at the completion of development, but does not allow for the limitations of manufacturing processes and procedures found on the factory floor. Hence, the apparently mature product configuration does not survive rate production without performance degradation, and significant redesign is required for efficient production. At M-C Power, the Engineering and Manufacturing Departments are working together to develop a product that is both producible and effective.

When designing the process, the first step is to review the requirements. After the design requirements have been reviewed for completeness and clarity, ideas are formulated on how to meet the cited requirements. Here, producibility is considered as part of the design criteria to be evaluated for cost-effectiveness and ease of manufacture versus the degree of compliance with the functional requirements.

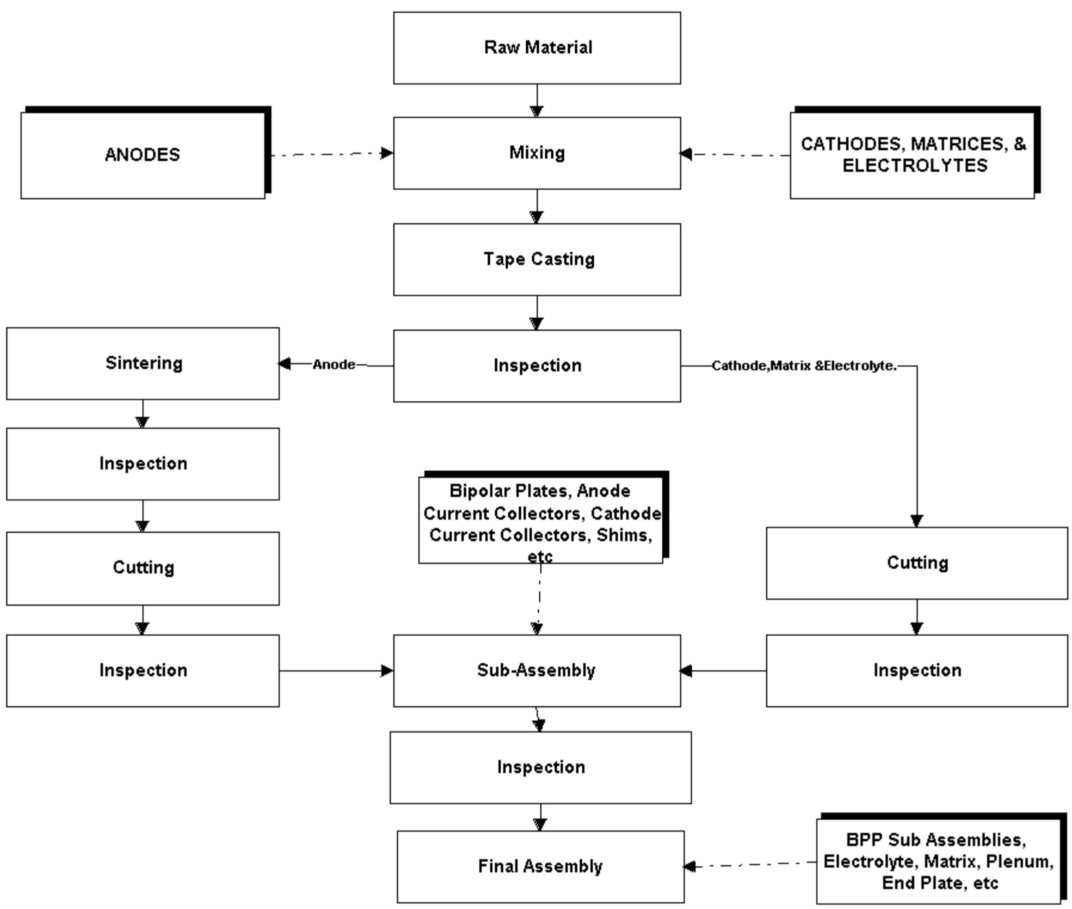
Detailed design documents require review by manufacturing. Released engineering documents require sign-off by manufacturing. In order to minimize the risk attributable to transition from development to production, requirements for joint engineering/development/manufacturing participation through-out the full-scale development phase are among the most critical. All documents that formed the design and manufacturing bill of materials are converted into operation sheets and process charts. These operations sheets and process charts allow us to establish a manufacturing process discipline for the fabrication of stack repeating elements. Samples of operation sheet title/revision pages are included with this report as Figure 1, Attachment 1. Process Charts can be found in Attachment 2.

The Technology Development Group and the Product Development Group are responsible for the development and control of the MCFC design and its internal and external components. Changes are handled via formal change requests, design, reviews and approvals. Document title sheets show revision numbers and approval levels.

By following the best engineering practice, M-C Power was able to convert a total manually operation to an automatic and semi automatic operation in some areas. More areas of improvement are currently being investigated.

Figure 2 shows a general representation of the steps needed to manufacture a MCFC stack. A brief description of the process to manufacture a MCFC and equipment description is also explained. Notice that the production capacity corresponding to any facility was calculated considering that each stack is composed of 250 cells, a performance of 115 Watt/Sq. ft. and 240 working days/year.

Figure 2. General Process Flow Chart



4.2.2.1 Mixing Operation:

In this process four repeat part components of a MCFC are produced, following detailed engineering specifications and bills of materials. These repeat part components are the anode, cathode, matrix and electrolyte (ACME). To obtain these elements with certain properties, the Technology Developing Group provides the Manufacturing Department with a formulation sheet that the operator follows to get a slip or slurry with the proper characteristics.

Previously, this operation was performed manually. The operator used to carry the drum or container with the raw material to be weighted onto a scale; then the operator manually added the requested raw material into the mixer at pre-determined times. This manual procedure results in obtaining the properties of the slip varying from one batch to another. Also, the operator was interacting with materials such as powders and liquids.

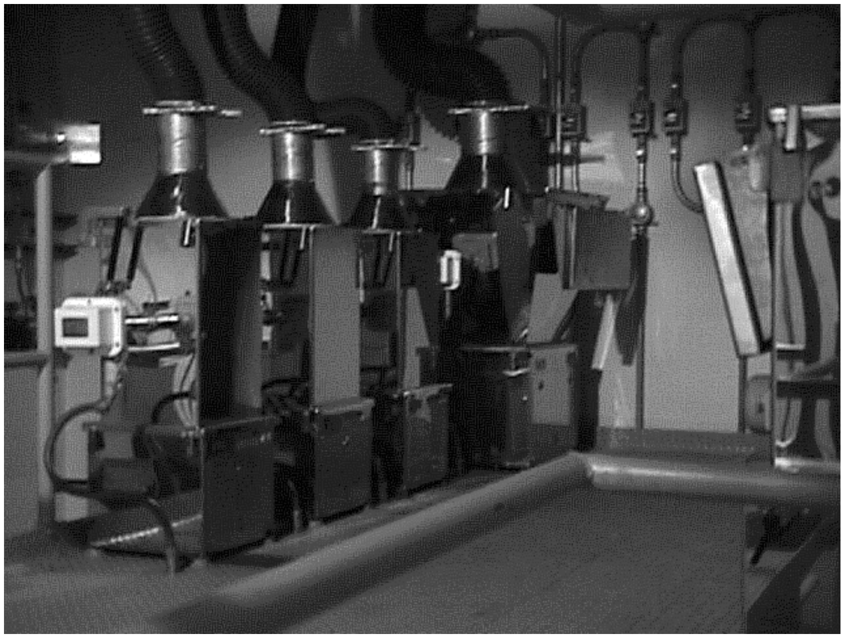
This year, the design and installation of an Automated Batch Mixing System (Figure 3) was completed which includes:

- Automated feeding of dry ingredients,
- Weighing and discharge of each dry ingredient into the mixers,
- Automated pumping weighing, and discharge of each liquid ingredient into the mixers,
- Underground slip delivery system from the mixers to the tape casters,
- And a supervisory control panel to operate all systems in either an auto or an manual mode.

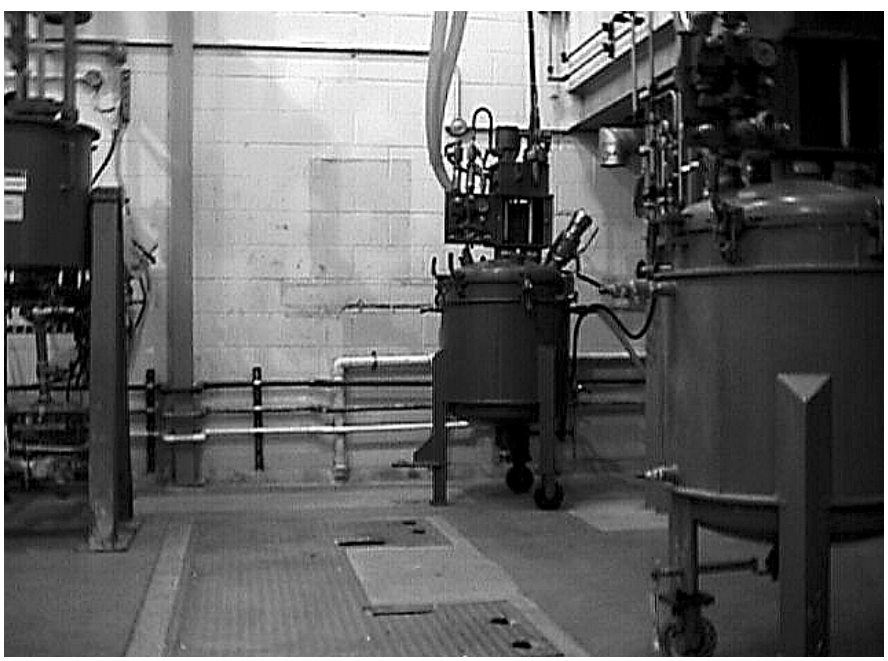
The Mixing Facility now is capable of mixing all four ACME components and both solvent-based and water-based systems with simultaneous direct feed to both tape casters. By automating the mixing procedure, mix repeatability and reproducibility will be increased. An added benefit is decreased worker exposure to potentially harmful materials due to decreased material handling. This automatic mixing system will enable M-C Power to monitor the mixing operation by establishing real time statistical process control.

Figure 3: MIXING FACILITY

(A) Powder Batching System



(B) Production Attrition Mill and 50 Gallon Mixers



4.2.2.2 Tape Casting Operation:

The slip obtained during the mixing operation is fed into a doctor blade reservoir (Figure 4). The physical characteristics of this slurry will determine the setting of the height of the doctor blade. The slurry is then extruded through the doctor blade forming a wet tape that flows though a drying process in the tape caster. The main parameters that govern this process are the zone temperatures, airflow rate, doctor blade height, and tape caster speed.

At the other end of the tape caster, a dried tape (commonly named green tape) is cut to length and then inspected for taking variable and attribute data; the thickness of a tape is measure along its transversal dimension every 1 inch. The tape casting facility is shown in (Figure5).

Figure 4. Tape Casting Operation

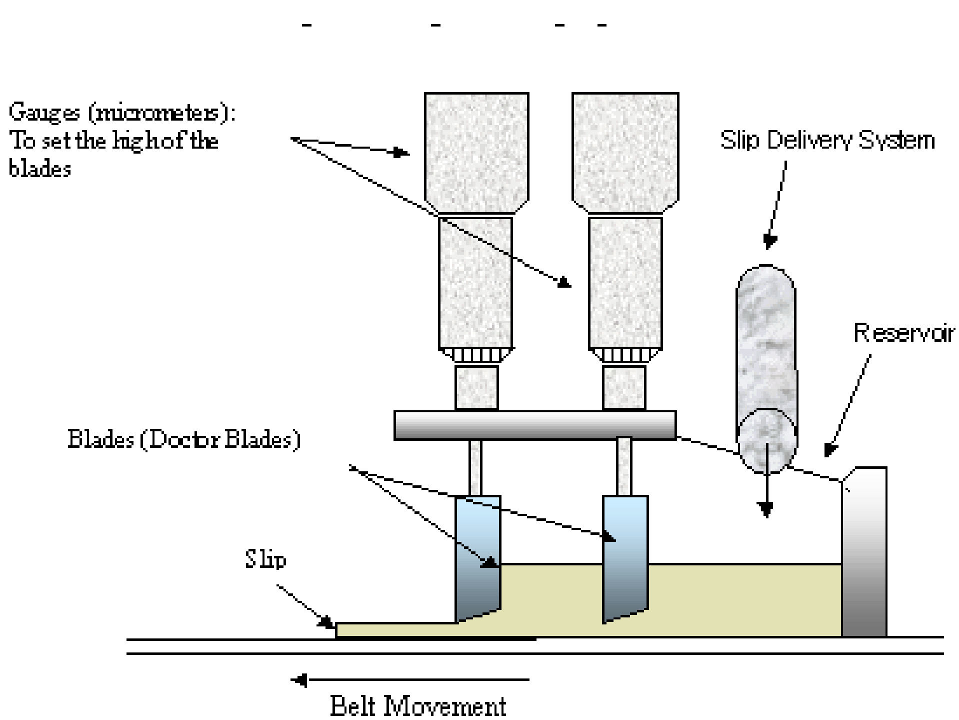


Figure 5: M-C Power Tape Casting Facility

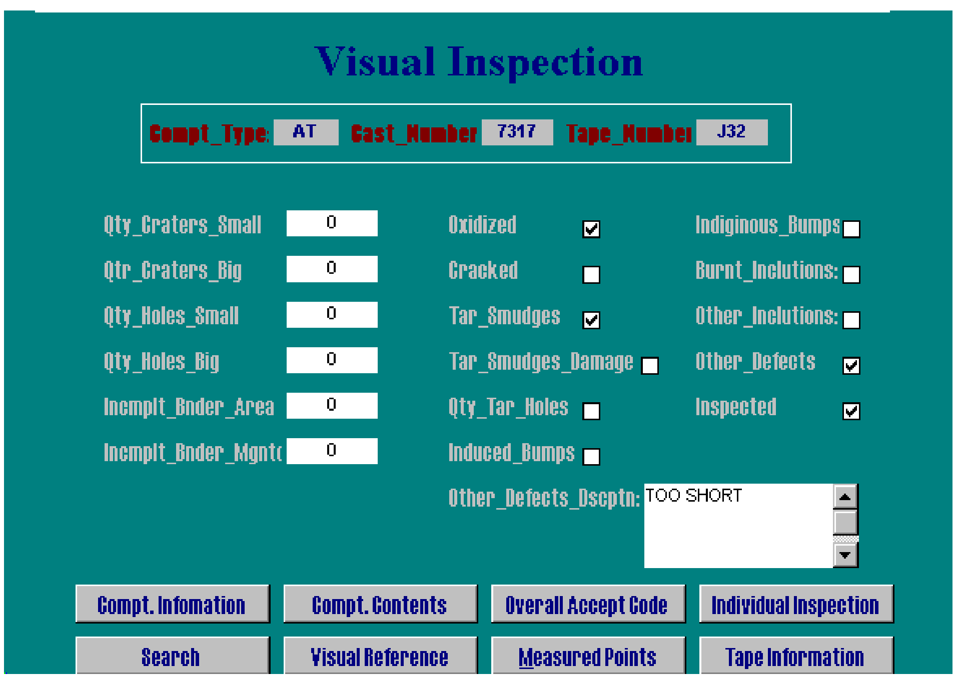
4.2.2.3 Sintering Operation:

After tape casting anode and cathode (if required) tapes are fed into a continuous belt sintering furnace (Figure 6). The reasons for sintering these components are: a) to burn out all of the residual organic materials after casting and b) to increase the component strength by sintering the metal particles together to form the electrode. Like the tape casting operation, several process parameters regulate the sintering process; these are sintering belt speed, zone heat temperatures (pre-heat and high heat section), flow rate and temperature of inert gases (H_2, N_2, and CO_2), and furnace load rate will give the electrode the desired strength, thickness and porosity.

After a tape has been sintered, this tape is 100% inspected for both variable and attribute criteria as shown in Figure 7. In the past, the thickness of the component was manually obtained by measuring in about 30 different positions. All measurement and visual inspection data were recorded and analyzed in a spreadsheet.

Figure 6: M-C Power Sintering Furnace

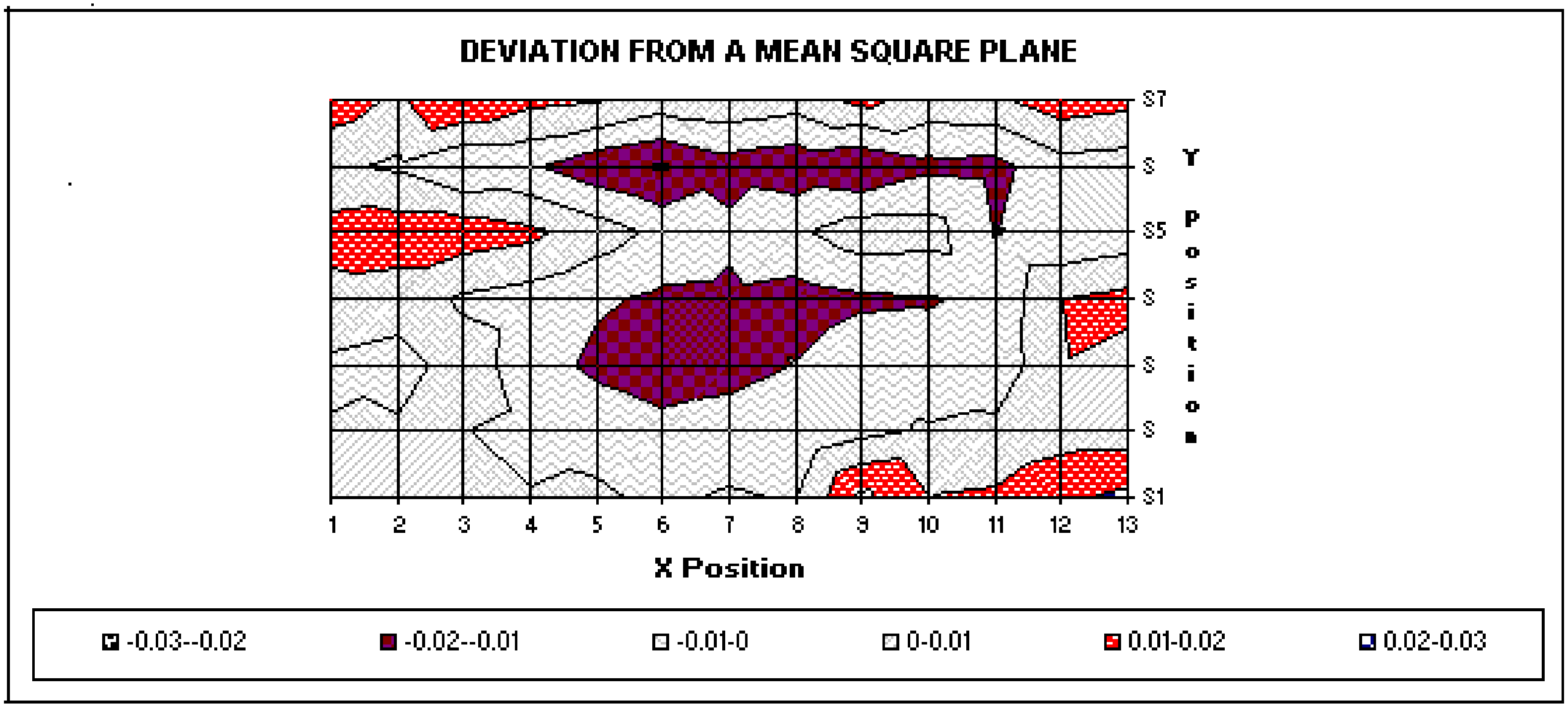
Figure 7: Sintering Operation Visual Inspection Form



Within the last year, the construction and qualification of the new Electrode Inspection System (EIS) was completed. The new system, shown in Figure 8, is a semi-automated, contact measurement system with integrated weighing and thickness inspection. This system includes a three (3) times increase in the number of thickness measurement points, with a 50% reduction in the inspection cycle time. A typical thickness map is shown in Figure 9. Gage repeatability and reproducibility (R&R) studies were completed on sintered anodes and cathodes verifying a five (5) times increase in the measurement accuracy compared to the previous non-contact measurement methods. All measurements and visual inspection data are recorded and analyzed. This system incorporates a database, which stores all of the measured data (weight, dimensions, thickness measurements, etc.) and inspection data (visual attributes) for each component. The data is analyzed using statistical process control charts and used to calculate thickness profiles, component porosities, and average component thicknesses. This data can then be integrated with ongoing engineering design, quality control and process control efforts.

Figure 8: Electrode Inspection System

Figure 9: Typical Thickness Map



4.2.2.4 Cutting Operation:

After anodes are sintered; and cathodes, matrix, and electrolytes are tape cast, tapes are cut to net shape. Several process parameters are set before starting to cut ACME components, such as die type and load requirement. The unsintered cut components are stored in special containers so the shrinkage phenomenon is minimized. The shrinkage of the tape component is a product of external environment such as temperature and humidity. The punch press facility is shown in Figure 10.

Figure 10: Punch Press

4.2.2.5 Sub-Contracted Operations:

Qualified and certified prime contractors and subcontractors make bipolar plates, current collectors, and non-repeat parts for M-C Power according to our technical specifications. M-C Power is responsible for the qualification and certification of the manufacturing processes, tooling, and design of these components.

M-C Power established partnerships with prime contractors for the following reasons:

a) Most of the processes performed by contractors required high technology machines for complicated high capital operations such as laser cutting, CNC cutting, aluminizing, heat treatment, laser welding, etc.
b) Also, in the case of non-repeat parts (NRP), a low production of these NRP components do not justify the investment of buying or leasing these machines.

Separator plates (Figure11), which provided the functions of structural support and manifolding for gas distribution, are fabricated using the following steps:

- Pressing: Sheet metal is pressed to form the gas flow passages, wet-seal surfaces, manifold regions and gas feed rails.
- Cutting, trimming, and welding: Parts are then cut, trimmed and joined, using computer guided lasers.
- Aluminization: The wet-seals are protected from corrosion by a commercial aluminization and heat treating processes.

Figure 11: Separator Plate

4.2.2.6 Subassembly Operation:

The first operation is cell subassembly. This operation consists of putting together several components such as a bipolar separator plate, shims, cathode current collector, cathode electrode, anode current collector, and anode electrode. This operation, that is manually performed, requires high levels of detail to properly assemble the components.

The next subassembly operation to be executed is intermediate plate preparation and subassembly. This operation consists of attaching shims, cathode and anode components, and cathode and anode current collectors to the intermediate plate.

4.2.2.7 Final Stack Assembly:

Final stack assembly (Figure 12) is considered the most time consuming operation in the fabrication of the MCFC. This operation takes place in a low-humidity dry room. During final assembly of a stack, two operations occur simultaneously. These are cell assembly and matrix/electrolyte sorting. The sorting operation consists of matching a set of electrolytes and a set of matrices. The condition to satisfy when matching electrolytes depends on the carbonate load requirement and total thickness requirement per cell. Matching matrices requires that the total thickness of these matrices is within specifications. Cell assembly operation consists of putting together the bipolar plate sub assembly and the sorted set of matrix/electrolyte components. End plates, gas distributed piping, insulation plates, power take-offs and tie-rods are added to complete final stack assembly (Figure 13).

Figure 12: Final Assembly Operation

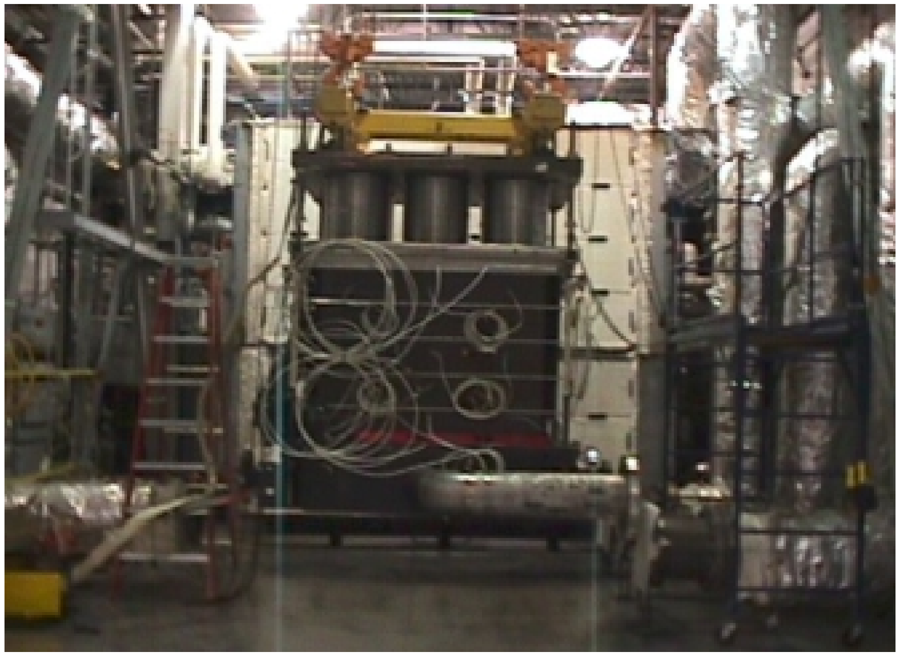
Figure 13: Stack Assembly

4.2.2.8 Testing:

After the stack is completely assembled, the stack is transported to the Acceptance Testing Facility (ATF- Figure 14) where instrumentation sets, piping , and insulation system is attached to the stack. Then, the stack is conditioned to remove the remaining binder from the matrix and carbonate, the carbonate is melted, and the stack is finally tested with actual power generation which ensures our technology meets performance goals before delivery.

Currently, the total stack installation, testing, and removal cycle is 35 days, which means that the ATF can support up to 10 stacks per year working 24 hours a day during 365 days per year.

Figure 14: Acceptance Test Facility (ATF)



4.2.2.9 Shipping

After acceptance testing, the MCFC is loaded back onto the air bearing cart and then transported to the portable dock which extends from the building into the parking lot. The stack is then lifted off the air bearing cart and placed into the bottom of the shipping container (Figure 15).

Figure 15: Shipping a Stack

4.2.3 Resource Requirements to Achieve Production Goals

The year 2001 production goal is to manufacture 4 stacks at 440 kW per stack, based upon schedule, and production capacity. Among all the features included within these MCFC stacks, the ones that should be mentioned are describe in Table 1. In this table, the scrap rates that we assumed are based on previous runs, and this scrap percentage is an accumulated value for the whole process. The manufacturing yield for each operation will be higher because of process improvements, reduction in variations, and automation.

Table 1: MCFC STACK FEATURE

Features of 441 KW Stack

1. 115 Watt/SF performance
2. 441 KW Stack manufactured
3. 330 cells per stack
4. 30 days for stack testing
5. 10 mandays for stack installation
6. 944 hours for assembly
7. Batch Mixing, TC, & Sintering
8. 4 stacks per year

	Anode	Cathode	Matrix	Electrolyte	Plates SA
Amount Per Cell	1	1	3	2	1
Amount Per Stack	330	330	990	660	330
Amount Per year	1320	1320	3960	2640	1320
All Process Scrap Rate	49%	19%	19%	19%	0%

The manufacturing resources required to achieve our goals can be divided into 5 groups:

4.2.3.1 Facilities

M-C Power's manufacturing facility, where the MCFC's are currently produced, is located in Burr Ridge, IL, a southwest suburb of Chicago. The operations performed at this location include component slip mixing, tape casting, sintering, die cutting, assembly, conditioning, and testing prior to shipment. This represents a total area of about 51,000 square feet from which almost 50% is allocated for manufacturing, warehouse, testing facility and labs. Based on previous studies, it was determined that the space requirement for a manufacturing capacity of 10 MW per year could be covered by our current layout. In Table 2, the estimated total required area was calculated based on the current dimension of existing equipment, labs, and other areas.

The facility includes all plant and capital equipment necessary to accomplish our production goal. These requirements are displayed in Table 2 and Table 3. The material flow within the plant from the stock/receiving area to the ATF/shipping area is shown in Figure 16. Because of the nature of our process which consists of batch manufacturing operations (one stack at the time), the in-process storage and material transit time is kept at a minimum level. Assuming that the average time to completely make a MCFC is to be about 6 weeks, the space required for in-process storage is sufficiently covered by our current plant (see Table 2).

To validate the plant capability requirement, a simulation model of our current manufacturing system was modeled. To build this simulation model, it was necessary to complete the following steps:

a Develop a process flow chart for every single operation. For instance, the first operation to manufacture a MCFC is to fill the hoppers in the mixing room with their respective raw materials. This operation consist of getting a pallet of this material from the warehouse, load it in the lift truck, transport the load to the mixing room, and fill up the hopper.

b After developing the flow charts, a time study was performed. The methodology used was the standard stop watch method; then allowances were given to each task.

c Build the simulation model taking into consideration the previous developed flow charts and time study. In some cases, production rates were assumed to be distributed either triangularly or rectangularity because no time study data was available for such an operation. For instance, the gluing time, when doing plate subassembly, was assumed to be triangularly distributed. Another consideration on this simulation model was to define the recipe to be used to manufacture the ACME parts. This was also important since in the model the conversion from volume or weight to number of pieces is done by a series of interpolation.

d Validate the simulation model by comparing with previous production runs.

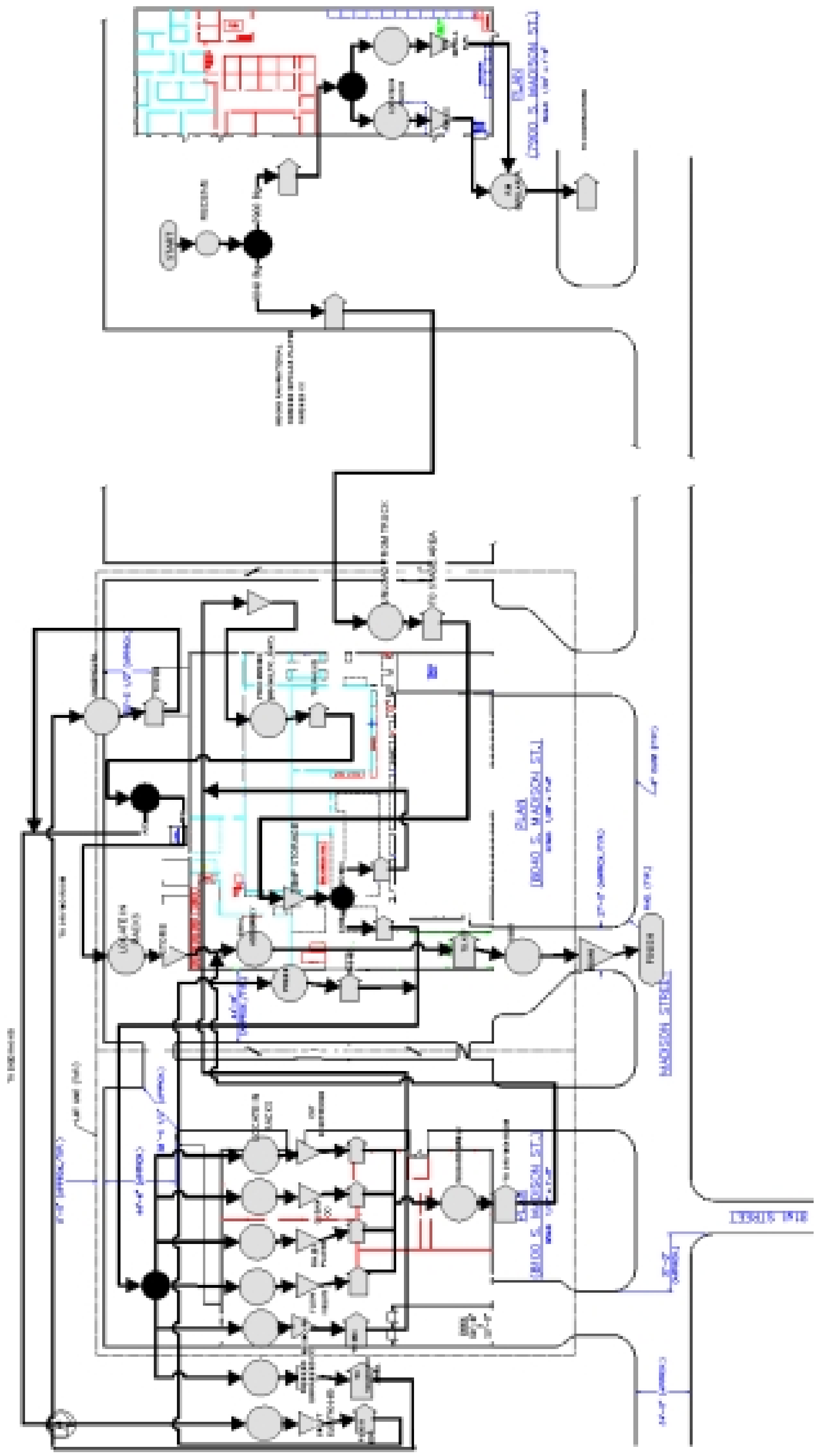
e Evaluate the simulation outputs.

Table 2

Facilities Requirement

Factory	*Per Unit Dimension*	#	*Sq Feet*
Raw Material	6 weeks of prodn		2,843
Work-in-Process	6 weeks of prodn		474
Finished Goods	6 weeks of prodn		474
Matl. Handling	1000	1	1,000
Maintenance	1000	1	1,000
Common Areas	1000	1	1,000
Lab Area	500	1	500
QC Inspection	500	1	500
Lunch/Lockers	500	1	500
			8,291
Equipment	*Per Unit Dimension*	#	*Sq Feet*
Mixing	350	2	700
Tape Casting	1500	2	3,000
Sintering	2500	1	2,500
Cutting	500	1	500
			6,700
Assembly	*Per Unit Dimension*	#	*Sq Feet*
Stack Assembly	1000	1	1,000
Pre Assembly	1000	1	1,000
Post Assembly	500	1	500
			2,500
Testing	*Per Unit Dimension*	#	*Sq Feet*
Gas store & piping	500	1	500
ATFs & Skids	500	1	500
ATF Control Room	500	1	500
Gas reducing stn	500	1	500
			2,000
General Offices	*Per Unit Dimension*	#	*Sq Feet*
Direct Staff	50	23	1,150
Indirect Staff	100	12	1,200
G&A Staff	100	11	1,100
			3,450
Total Sq Feet Required			***22,941***

Figure 16. M- C Power Current Layout –Material Flow



4.2.3.2 Manufacturing Technology

To support the projected requirements, the machinery and equipment requirements are calculated. In the calculations, the scrap rate from previous runs was used as well as the same cell design used in the last run for manufacturing a MCFC. However, in this calculation an increase in tape casting and sintering speed was considered. In Table 3, the projected machine and equipment requirement are displayed. The current equipment and machine availabilities are:

a) Two 10 Gal and two 50 Gal Mixers. To meet projected demand, it is required to operate mixers two (2) shifts per day, and five (5) days per week.
b) Two 52-inch wide continuous tape casters (78 feet and 85 feet long) running at 20 inch per minutes for two (2) shifts per day, and five (5) days per week.
c) One sintering furnace of 70 feet long running at 8 inch per minute for three (3) shifts per day, and five (5) days per week.
d) One punch press running two (2) shifts per day, and five (5) days per week.
e) One Acceptance Testing Facility (ATF) running for three (3) shifts per day, and five (7) days per week.

Table 3: ACME EQUIPMENT & MACHINE REQUIREMENT

Mixing Operation	Anode	Cathode	Matrix	Electrolyte
Tapes to be processed	1972	1577	4728	3152
Loss in the Mixer	2.00%	2.00%	2.00%	2.00%
Mixing Batch Size (gallons)	30	10	10	35
Batch Prep & Mixing Operation	7	8	7	7
Number of Tapes from above batch	39	16	29	64
Total Mixing hours needed (hrs)	354	782	1157	343
Mixing Production (days)	23	49	73	22
Total Batch mixers needed	1	1	1	1
		Total Mixer Days	***95***	

Tape Casting	Anode	Cathode	Matrix	Electro
Tapes to be processed	1932	1545	4633	3088
Tape Casting length (inch)	82	60	67	67
Tape Casting width (inch)	47	36	45.5	45.5
Tape Casting speed (in/min)	20	20	20	20
Time reqd to TC 1 pc (mins)	4.1	3	3.35	3.35
Scrap Rate	10.00%	10.00%	10.00%	10.00%
Total minutes need (inclu scrap)	7921.2	4635	15520.55	10344.8
Startup (shifts)	2	1	3	2
Startup & Manufacturing (days)	10	6	18	12
Tape Caster Length (feet)	82	82	82	82
Release time - Inc all shifts (hrs)	49.2	49.2	49.2	49.2
Release time (in percent)	3.42%	3.42%	3.42%	3.42%
Total Prodn (days)	11	7	19	13
Number of Tape Casters	***2***	***TC Days***	***32***	

Sintering	Anode	Cathode	Matrix	Electro
Tapes to be processed	1738	n/a	n/a	n/a
Sintering length - inches (pre-diff)	108	n/a	n/a	n/a
Sintering speed - in/min	8	n/a	n/a	n/a
Time reqd to Sinter 1 pc	13.5	n/a	n/a	n/a
Scrap Rate	20.00%	n/a	n/a	n/a
Total minutes need (Inc Scrap)	23463	n/a	n/a	n/a
Startup (shifts)	4	n/a	n/a	n/a
Sintering Prodn (days)	27	n/a	n/a	n/a
Total Sintering Furnaces ***1***		***Total Sintering Days=***	***27***	

Cutting	Anode	Cathode	Matrix	Electro
Tapes to be processed	1390	1390	4169	2779
Cutting speed (sheets/hr)	10	10	8	10
Time reqd to Cut 1 pc (min)	6	6	7.5	6
Scrap Rate	5.00%	5.00%	5.00%	5.00%
Total minutes need (Inc Scrap)	8340	8340	31267.5	16674
Die Changing (shifts)	1	1	3	2
Total Prodn (days)	10	10	35	19
Total Cutting Machines ***1***		***Total Cutting Days =***	***74***	

Table 3: ACME EQUIPMENT & MACHINE REQUIREMENT (Continued)

Bi-Polar Plate SubAssembly / Final Assembly	
BPP and Cell Assembly (min/cell)	151
Stacking assembly (min/cell)	10
Total assembly time (hrs/stack)	885.5
Total Hours needed	3542
Total Hours Per Year Available	3840
Total stack assembly cells needed	1
NRP Addition/ATF setup/Shipping	
NRP assembly in ATF (hrs/men)	38
Post ATF/Ship (hrs/men)	20
Total Final assembly time (hrs/men)	58
Total Hours need	232

Testing	
Steps for Test/Condition	**hrs**
1. Piping, instr, insulation	86.4
2. Binder Removal	201.6
3. Elec melt, cathode oxid	288
4. Acceptance Test	72
5. Cooldown	36
6. Enclo removal & analysis	36
Stack Testing for 30 days	720
Total Hours need	2880
No of Stacks/ATF/Year	11.2
No of ATF's needed	1

4.2.3.3 Manpower

This includes those managing the project, design engineers, manufacturing engineers, quality engineers, testing engineers, and direct and indirect labor personnel. For better understanding, the people required to run this project can be divided into three groups:

a) *Direct Labor*.- This includes the manpower needed to completely manufacture a stack. These are defined as manufacturing/assembly technicians and testing technicians. Production supervisors are considered as an addition to the direct labor.
b) *Indirect Staff*.- All the personnel that support the manufacturing of a MCFC and who do not work on the manufacturing line are considered indirect staff. These are field engineers, manufacturing support, design engineers, drafting specialists, facility and equipment maintenance technicians, and quality assurance engineers. *The Field Engineer* is the person responsible for installation of the MCFC in the power plant facility. *Manufacturing Support* are those people responsible for optimizing the manufacturing methodology (through fixtures, equipment, improving methods, etc.), industrial engineering tasks (time study, line balancing, simulation, plant layout, etc), developing new way to make things, production schedule, inventory control, etc. These are the manufacturing engineers, and manufacturing planners. *Design Engineers* are those responsible for designing the product, selecting materials, and setting specifications. This group is formed by mechanical engineers, electrochemical engineers, chemical engineers, and material engineers. *Quality Engineers* are those responsible for qualifying material, equipment & process, design of experiments, statistical process control, etc.
c) *G&A Staff*.- All the people not related to manufacturing or design of a MCFC power plant are considered in this group. These are the president and vice presidents of the company, directors, secretaries, project managers, sales and marketing representative, accounting staff, purchasing and receiving, etc.

The personnel requirement for this project is shown in Table 4.

Table 4: People requirement

DIRECT LABOR (Description)	Men Per Operation	No. of Shifts	Number of Operation Days	Man-Hours	Avg Employee Req. Per Year
ACME COMPONENTS					
Mixing/Tape Casting	6	2	95	9,120	5
Sintering	2	2	27	864	1
Cutting	2	2	74	2,368	2
	ACME Manuf. Man-Hours			12,352	
	ACME Employees Required				8
SUB ASSEMBLY AND ASSEMBLY					
Assembly	5	2	222	17,710	10
	Assembly Man-Hours			17,710	
	Assembly Employee Required				10
TESTING					
In/Out ATF/Ship	4	2	15	960	1
Testing	3	3	120	8,640	5
	In/Out ATF/Ship & Testing Man-Hours			9,600	
	In/Out ATF/Ship & Testing Employees Req.				6
Prod Supervisors	1	3			3
TOTAL DIRECT LABOR:				***39,662***	***27***

Table 4: People requirement (Contimue)

INDIRECT STAFF	
Field Engineers	1
Man'f Support (Mnf Eng,Inventory,etc)	7
Design/Drafting (Prod.Dev.&Tech.Develp)	15
Equip/Facility Maintn	3
Quality(Mng, Engineers)	4
Total Indirect Staff	***30***
G & A STAFF	
Administration(President, Sec, Asst.)	4
Sales & Mktg & Project Management	6
Accounting	4
Purchasing	1
Secretaries	2
Total G&A Staff	***17***

4.2.3.4 Schedule Definition

A schedule is meant to provide assurance that the necessary resources will be available when needed, that no resources will be overloaded or expended during execution of any manufacturing tasks, and that production delivery dates are indeed achievable. Special attentions are paid to areas having potential impact on the MCFC delivery schedule (in terms of either quantity or time). These areas are engineering release, material procurement, tool design, fabrication, and prove-out; and test equipment prove-out.

4.2.3.5 Material Requirement Planning (MRP) System.

In the transition from small scale, short run manufacturing to full sale batch manufacturing, complete quantities of raw materials were ordered. To correctly manage these materials, a MRP system was established during repeat part manufacturing runs and are continuously improved and updated by the manufacturing planner. The MRP development consists of:

a) Determining requirements of finished products, the Master Production Schedule (Table 5) from current contract forecast.
b) Using the Bill of Materials, calculating the gross requirements for each item, beginning with the item at level zero (Table 6).
c) Determining, using the Bill of Materials file and the Individual Inventory Tickets (Table 7), the order release dates and the order quantities for each item necessary to meet the Master Production Schedule.
d) Regeneration of the MRP on the basis of changes in the Master Production Schedule according to priorities.

Once established, this information is then incorporated into a computerized MRP spread sheet program. Based upon the calculated usage rates, the MRP System is capable of automatically deducting material quantities consumed on a per cast basis to give ending inventory. This information is then utilized to determine material reorder schedules and quantities.

All the raw materials, work in process, and finish product are assigned to a specific location in the warehouse area. Each product, load, or pallet can be easily located in another spread sheet program that is linked to the MRP program.

Even though our current MRP system satisfies our current needs, this system is incapable of managing large production volume such as a continuous production mode. In addition, our current system does not integrates sales, inventory control, finance, manufacturing, and management. Currently, M-C Power does not have a computer system that both integrates all of these functions, and maintains and upgrades periodically, which saves a lot of time and money. For this reason, M-C Power is considering acquiring an Enterprise Resource Planning (ERP) System that would prepare us for the future. One key benefit of ERP systems is the way it integrates a company's flow of information. Using an ERP system, the sales, purchasing, production, inventory control and accounting departments all use the same information. Centralizing this information and presenting it consistently can also improve planning and decision making. By implementing an ERP system, M-C Power will also reduce the cost of a MCFC. The reality behind this last statement is because manufacturers with fully functional ERP systems report the following benefits:

- Reduced inventories 50%
- Reduced order-cycle times 43%
- Increased production capacity 36%
- Lower total logistics costs 32%
- Decreased procurement costs 29%
- Reduced manufacturing waste 29%
- Lower distribution costs 14%

Table 5: Manufacturing Weekly Actuals

OPERATION	PRODUCT		1/3/00	1/10/00	1/17/00	1/24/00	1/31/00	2/7/00	2/14/00	2/21/00	2/28/00	3/6/00	3/13/00	3/20/00	3/27/00	*TOTAL*	
TAPE CASTING	ANODE	**Plan**	0	195	195	195	156	0	0	0	0	0	0	0	0	741	**Plan**
		Cum Plan	0	195	390	585	741	741	741	741	741	741	741	741	741	741	**Cum Plan**
		Actual														0	**Actual**
		Cum Actual		0	0	0	0	0	0	0	0	0	0	0	0	0	**Cum Actual**
		Balance	0	195	195	195	156	0	0	0	0	0	0	0	0	741	**Balance**
		Cum Balance	0	195	390	585	741	741	741	741	741	741	741	741	741	741	**Cum Balance**
	CATHODE	**Plan**	0	0	0	0	0	104	104	104	104	104	104	0	0	624	**Plan**
		Cum Plan	0	0	0	0	0	104	208	312	416	520	624	624	624	624	**Cum Plan**
		Actual														0	**Actual**
		Cum Actual		0	0	0	0	0	0	0	0	0	0	0	0	0	**Cum Actual**
		Balance	0	0	0	0	0	104	104	104	104	104	104	0	0	624	**Balance**
		Cum Balance	0	0	0	0	0	104	208	312	416	520	624	624	624	624	**Cum Balance**
	MATRIX	**Plan**	0	192	192	192	192	192	192	192	96	0	0	0	0	1440	**Plan**
		Cum Plan	0	192	384	576	768	960	1152	1344	1440	1440	1440	1440	1440	1440	**Cum Plan**
		Actual														0	**Actual**
		Cum Actual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**Cum Actual**
		Balance	0	192	192	192	192	192	192	192	96	0	0	0	0	1440	**Balance**
		Cum Balance	0	192	384	576	768	960	1152	1344	1440	1440	1440	1440	1440	1440	**Cum Balance**
	ELECTROLYTE	**Plan**	0	0	0	0	0	0	0	0	0	544	476	0	0	1020	**Plan**
		Cum Plan	0	0	0	0	0	0	0	0	0	544	1020	1020	1020	1020	**Cum Plan**
		Actual														0	**Actual**
		Cum Actual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**Cum Actual**
		Balance	0	0	0	0	0	0	0	0	0	544	476	0	0	1020	**Balance**
		Cum Balance	0	0	0	0	0	0	0	0	0	544	1020	1020	1020	1020	**Cum Balance**
	TOTAL PLAN		***0***	***387***	***387***	***387***	***348***	***296***	***296***	***296***	***200***	***648***	***580***	***0***	***0***	***3825***	***TOTAL***
	HEADCOUNT		**6**	**6**	**6**	**6**	**6**	**6**	**6**	**6**	**6**	**6**	**6**	**6**	**6**		**TOTAL**
	SHIFTS		**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**		**TOTAL**
SINTERING	ANODE	**Plan**	0	165	165	165	132	0	0	0	0	0	0	0	0	627	**Plan**
		Cum Plan	0	165	330	495	627	627	627	627	627	627	627	627	627	627	**Cum Plan**
		Actual														0	**Actual**
		Cum Actual		0	0	0	0	0	0	0	0	0	0	0	0	0	**Cum Actual**
		Balance	0	165	165	165	132	0	0	0	0	0	0	0	0	627	**Balance**
		Cum Balance	0	165	330	495	627	627	627	627	627	627	627	627	627	627	**Cum Balance**
	TOTAL PLAN		***0***	***165***	***165***	***165***	***132***	***0***	***0***	***0***	***0***	***0***	***0***	***0***	***0***	***627***	***TOTAL***
	HEADCOUNT		**3**	**3**	**3**	**3**	**3**										**TOTAL**
	SHIFTS		**2**	**2**	**2**	**2**	**2**										**TOTAL**
CUTTING	MATRIX &ELECTRO	**Plan**	0	0	0	0	0	0	0	0	0	300	300	300	300	1200	**Plan**
		Cum Plan	0	0	0	0	0	0	0	0	0	300	600	900	1200	1200	**Cum Plan**
		Actual														0	**Actual**
		Cum Actual														0	**Cum Actual**
		Balance	0	0	0	0	0	0	0	0	0	300	300	300	300	1200	**Balance**
		Cum Balance	0	0	0	0	0	0	0	0	0	300	600	900	1200	1200	**Cum Balance**
	HEADCOUNT											**2**	**2**	**2**	**2**		**TOTAL**
	SHIFTS											**2**	**2**	**2**	**2**		**TOTAL**
MANPOWER	**REQUIRED**		**9**	**9**	**9**	**9**	**9**	**6**	**6**	**6**	**6**	**8**	**8**	**8**	**8**		
	EXISTING TECHS.		**4**	**4**	**4**	**4**	**4**	**4**	**4**	**4**	**4**	**4**	**4**	**4**	**4**		
	BALANCE		**5**	**5**	**5**	**5**	**5**	**2**	**2**	**2**	**2**	**4**	**4**	**4**	**4**		

ASSUMPTIONS:

1. 75% MATERIAL YIELD AT TAPE CASTER.
2. 70% PROCESS YIELD AT SINTERING.
4. MFG. SCHEDULED ON 2 X 8 X 5.
6. ADDITIONAL TECHNICIANS TO SUPPLEMENT FOR VACATIONS AVAILABLE.

Table 6: Materials Resources Planning

CURRENT MATERIALS									ANODE		CATHODE		MATRIX		ELECTROLYTE		Chemical
			1999 Production Tapes Requirement														
Material	End Inv.(kgs.)	Min Tapes	Anode 300 1 50%	Cathode 300 1 20%	Matrix 300 3 20%	Electrolyte 300 2 20%	need inv	balance	Avg. (kg./tape)	Rem. tapes	Avg. (kg./tape)	Rem. tapes	Avg. (kg./tape)	Rem. tapes	Avg. (kg./tape)	Rem. tapes	1999 Lead-Time
San 160	266.75	4660	600	375	1125	750	142	125	0.0484	5512	0.0448	5957	0.0572	4660	0.0420	6352	**3 - Weeks**
Methocel K35LV	181.44	981	600	375			170	12	0.1849	981	0.1567	1158					**3 - Weeks**
Ethylene Glycol	208.17	2373	600	375			75	133	0.0877	2373	0.0597	3487					**3 - Weeks/TAB 2-DAYS**
GP-1000S	13.50	0					0	14									
Propanol	51.60	94	600	375			386	-335	0.5507	94	0.1493	346					**1- Day**
Ni-287	2524.86	619	600	375			3883	-1358	4.0805	619	3.8246	660					**1WK - 2Mths**
Fine Cr. Solution	137.28	597	600				138	-1	0.2301	597							
El Chrome	319.95	2222	600				86	234	0.1440	2222							**3 - Weeks**
Calcium Carbonate	12.70	66		375			72	-59			0.1925	66					**3 Weeks**
Ni-255	3172.50	829		375			1434	1738			3.8246	829					**1 - Week**
HSA-10	378.95	345			1125		1235	-856					**1.0978**	345			**1 Week**
Saffil	133.30	768			1125		195	-62					0.1736	768			**6 - 8 Weeks**
Alumina Satellites	127.41	11583			1125		12	115					0.0110	11583			**2 - 4 Weeks**
Emphos PS-220a	199.82	12381			1125	750	44	156					0.0161	12381	0.0340	***5877***	
Witflow 918	400.26	37340			1125	750	11	389					0.0028	142531	0.0107	***37340***	**1- Week**
M1112	63.32	985			1125	750	85	-22					0.0643	985	0.0171	3704	**4 Weeks**
B73196(Elvacite Soln.)	468.85	318			1125	750	2292	-1823					1.4755	318	0.8427	556	**4 - 6 Weeks**
Carbon Beds	2.00	300			1125	750	11	-9					**0.005**	**400**	**0.007**	**300**	**1 Week**
Toluene	278.13	4565			1125	750	67	211					0.0188	14828	0.0609	4565	**1- Day**
1-Butanol	200.20	21122			1125	750	28	172					0.0188	10673	0.0095	21122	**1- Day**
Naptha	243.30	15744			1125	750	17	226					0.0048	51164	0.0155	15744	2 - Days/ 1 Day ChemCentral
Flourescein Dye	0.35	1638				750	0	0							0.0002	1638	**7 Days**
LI-NA	498.80	233				750	1603	-1104							2.1368	233	**6 - 8 Weeks**

DATE: **10/20/99**

Table 7: Inventory Ticket

INVENTORY TICKET

MATERIAL: Ni 287 UNITS= KGS. MIN. QTY= 10

INCOMING				OUTGOING					BALANCE
DATE	IM NUMBER	BARREL NO	QUANTITY	DATE	CAST NO.	IM NUMBER	BARREL NO	QUANTITY	QUANTITY
10/29/97			164.86					24.05	***140.81***
12/08/97	0172							12.85	***127.96***
02/05/98			10.88					12	***126.84***
								29.25	***97.59***
				04/14/98	EJH			1	***96.59***
				04/15/98	M8105			1.125	***95.47***
				04/30/98	Dev. Grp(SG)	0136	01	1.5	***93.97***
				05/04/98	Dev. Grp(SG)	0136	01	1.5	***92.47***
05/21/98	0195	01	226.75	05/05/98	Dev. Grp(SG)	0136	01	1.5	***317.72***
								29.48	***288.24***
				03/17/99	Tape-Debug	0136	01	0.6	***287.64***
				04/15/99	CU9105	0136	01	0.7	***286.94***
				05/19/99	CU9139	0136	01	0.7	***286.24***
				05/27/99	CU9148	0136	01	0.7	***285.54***
				06/07/99	CU9158	0136	01	0.7	***284.84***
				09/27/99	INV. ADJ.	0136	01	18.088	***266.75***

4.2.4 Hazardous Raw Materials

Some of these materials require special storage and/or material handling procedures that are properly documented. Table 8 identifies all those materials currently used for production. The Material Safety Data Sheets of each of these raw materials are available.

Table 8: Raw Material Consumption and Safety Data

RAW MATERIAL (*)	AMOUNT REQUIRED (KG)	HAZARDOUS MATERIAL	FLAMMABLE / EXPLOSIVE MATERIAL	STABLE MATERIAL
Anode Current Collector (Foam)	15,352	NO	NO (When isolated from Reactive Materials)	YES
Ni-287	10,473	YES	NO (When isolated from Reactive Materials)	YES
16.0 mil 310 SS Ni/Clad matl	7,941	NO	NO	YES
16 mil 310 SS Flow Field	7,941	NO	NO	YES
16 mil 310 SS CCC	7,941	NO	NO	YES
Binder MSI B73196	6,565	YES	YES (75% Solvent Solution)	YES
Physical Mixture Techgrade Li/Na Powder	6,467	YES	NO (When isolated from Reactive Materials)	YES
DI Water	6,050	NO	NO	YES
HSA-10 LiAlO2 Vendor Powder	3,018	YES	NO (When isolated from Reactive Materials)	YES
N Propanol	1,139	YES	YES	YES
Methocel K35	506	YES	YES. When air concentration level > 0.03 oz/cu ft.	YES
Saffil	490	YES	NO	YES
Santicizer 160	469	YES	NO	YES
Ethylene Glycol	264	YES	YES	YES
Toluene	262	YES	YES	YES
M1112	234	YES	YES	YES
Calcium Carbonate	214	YES	NO. No specific info available when mixed with other materials	YES
Electrolytic Chrome	197	YES	YES. When air concentration level > 230 g/m3	YES
Withflow 918	91	YES	NO	YES
VMP Naphtha	67	YES	YES	YES
Butanol	41	YES	YES (Solvent)	YES
Fluorescein Dye	1	NO	YES. When air concentration level > 230 g/m3	YES

Note: *Material Safety Data Sheets (MSDS) for all these products are available. They may be submitted if requested.*

4.2.5 Capacity Constraints of Manufacturing Processes

4.2.5.1 Batch Mixing - This year, the design and installation of an Automated Batch Mixing System was completed that will support 10MW per year of production

4.2.5.2 Tape casting - Within the last year, the capability of significantly increasing the tape casting rates from 10 inch per minute (the standard rate for the MCP-8 manufacturing run) to 20 inch per minute was demonstrated. Studies were completed on the product formulations, the tape caster process air and exhaust flows, temperature distributions within the casters, and ventilation using the water-based cathode formulation as a basis. The studies revealed existing equipment deficiencies that were modified to improve the drying capability. Equipment qualifications were completed for the electrolyte and electrodes, with matrix qualification currently in process. Doubling the speed on the tape caster benefits M-C Power in its effort to increase productivity and to reduce cost by increasing the output and reducing fuel and energy consumption. Additional studies to reduce process variability are continuing. By upgrading the M-C Power Tape casting Facility, this operation can support up to 20 MW per year (Figure 5).

4.2.5.3 Sintering - In order to better balance the factory operations and increase the total ACME manufacturing capacity, furnace design changes were necessary. The sintering furnace is in the process of being rebuilt with modifications which will decrease the mean-time-between failures to 5 years as a minimum, and will allow increased belt speeds of at least 8 inches per minutes. Furthermore, the developing of a cathode electrode that does not need go through the sintering operation is another achievement that reduces the gas and energy consumption, increases our production capability, and minimizes the release of organic elements during sintering. These two improvements combined enable the Sintering Furnace Facility to increase its output from 7 MW /Year to 25 MW/Year.

4.2.5.4 Cutting - The punch press facility can currently can support up to 8MW/Year. More experience, training, and facility layout could increase the cutting facility to 10 MW/Year.

4.2.5.5 Cell Subassembly - Currently, a subassembly work cell can support an estimated production of 9 MW/Year. The production capacity could easily reach 10 MW/Year if 4 additional subassembly tables were added to the cell assembly operations.

4.2.5.6 Stack Assembly - Currently, a final assembly work cell can support an estimated production of 4 MW/Year. The production capacity could easily reach 10 MW/Year if two (2) additional cell assembly tables were added to the assembly facility.

4.2.5.7 Other Facility Resources - Based on the data shown in Table 2, it has been determined that the current manufacturing facilities can support a manufacturing capacity of 10 MW per year.

5. MANUFACTURING IMPROVEMENT PROGRAM

The Manufacturing Department has initiated a series of improvements in order to accommodate future production. These improvements, which are either in progress or complete lead to:

- Increased Safety.
- Improved Quality.
- Increased production rate.
- Decreased cost.

Many of the improvements stated in the following subtitles have driven M-C Power to secure the following achievements:

- Reduced operator exposure to materials.
- Reduced Material Handling.
- Increased quality yields.
- Increased ACME production capacity by 100%.
- Reduced material cost by either replacing/eliminating materials or eliminating processing.

5.1 Achievements in Process Improvement and Cost Reduction

5.1.1 Facilities and Equipment

5.1.1.1 Mixing and Tape Casting

The following improvements were made to the tape casting and mixing areas during repeat component manufacturing runs:

a) Two (2) 50 gal mixers procured and installed.
b) Mixing room modified to incorporate larger (50 gal.) mixers.
c) New Automated Component Batch Mixing System capable of mixing two (2) different components and then feeding two tape casters. This improvement has shifted this operation from manual to automated operation and from attended to unattended operation.
d) Upgraded both tape casters to improve drying capacity, increase zonal control, and increase belt speed by a factor of 2.
e) Anti-static air knife added to take-off end to eliminate/reduce chips and to improve release.
f) Fabricated and installed carbon bed platforms above tape casters to accommodate effluent from the two (2) tape casters.
g) Procured a new computerized viscometer to better control mixing operation.

5.1.1.2 Sintering Furnace

a) Upgraded Sintering Furnace to improve process and increase output.
b) Increase output by a factor of 2.
c) Installed quick change entry door transition wedge, where heavy organic elements tend to deposit.
d) Installed pre-heat section gas humidifier for more complete binder removal.
e) Installed new pre-heat section muffle.
f) Built an Electrode Inspection System capable integrating weighing and thickness inspection. This equipment improves repeatability, reproducibility and reliability of the inspection operation. Another advantage of this equipment is that it reduces cycle time and level of effort. Finally, this equipment is capable of performing a real time statistical process control for the sintering operation.

5.1.1.3 Punch Press

a) Qualified a punch press which allowed the trim press operation to be done internally. In the past, this operation was delegated to an outside vendor. By performing this operation internally we have much better control over this operation and quality has been improved. This alleviated repetitive material handling and reduced scrap from handling, transportation, and storage.

b) Attached safety features to the punch press.

5.1.2 Preventive Maintenance

In order to maximize equipment up-time and ensure and improve equipment and process capabilities, quality, and production rates, M-C Power established a preventative maintenance program. Procedures and plans to properly maintain and modify our equipment on monthly, quarterly, and yearly basis have been implemented.

5.1.3 Assembly Issues

5.1.3.1 Identification of Issues Associated with Handling Large Area-Thin Components

The two major issues associated with handling material were:

a) The ability to store matrix and electrolyte tapes long term without adversely affecting properties, and
b) The ability to transport and store all work-in-process components.

The solutions to the above issues were:

a) Place the uncut and cut matrix and electrolyte components in vapor barrier bags which are impermeable to moisture. Five (5) desiccant bags are then placed into the bags which are purged with dry Nitrogen to evacuate air, and then to heat seal the bags shut. After sealing, the bags are stored on storage shelves in a humidity controlled room.
b) Reformulate the matrix and carbonate binder/plasticizer for long term storage.

5.1.3.2 Detailed Design of Stack Assembly Area

To transport the assembled stack from the dry room assembly area to the Acceptance Test Facility (ATF), a 60,000 lbs. capacity air bearing cart was designed and procured. This cart is capable of floating and steering the stack from the stack assembly area to the ATF. After testing, the stack is transported to a portable dock for shipping. The air bearing consists of a thin continuous cushion of air at low pressure applied over a relatively large area. Two synchronized drive wheels controlled by dual pendants provide directional control.

5.1.3.3 Fabricate Full-Area and Full Height Stack Assembly Rig

This objective involved improvement of stack assembly operations, and the design and fabrication of Cell/Stack Assembly tooling and equipment. Examination of the cell/stack assembly process requirements showed the need for mechanization, allowing the elimination of much of the arduous, direct hand labor involved during the assembly process of cells and stacks.

In partnership with an external vendor, M-C Power Corp designed and fabricated a Semi-Automated Pick and Place Cell Handling System for MCFC components. This system consists of a pneumatically operated cell gripper capable of picking up an individual cell subassembly package and placing it on top of another cell subassembly package to produce stacks.

Integrated with this equipment, robust tooling and fixturing alignment columns were also installed; this ensures that the stack is perpendicularly aligned as it is assembled. The use of this cell automation handling system alleviates repetitive labor and also it reduces assembly cycle time.

5.1.4 Material Processing

a) Eliminated Cathode Sintering.- Eliminating cathode sintering results in significant decreases in the labor, materials, and overhead costs due to elimination of the sintering/heat treating manufacturing process which increases yields and throughput. This concept has been proven in over six 100 B cm2 cell tests. Full-area casting and storage trials have been completed. Remaining work involves characterizing the creep and compaction characteristics as a function of the porosity and powder type.

b) P*hysically Mixed Technical Grade Carbonates*.- Replacing reagent-grade, pre-melted carbonates with physical mixtures of technical grade carbonate powders has been tested at the 100-cm2 level without impacting cell performance or endurance. This would reduce the cost to manufacture the electrolyte. A search for alternate suppliers revealed seven different companies able to supply Li_2CO_3 and Na_2CO_2 powders in bulk quantities. Vender selection was based on cost, impurity types and contents, and particle sizes.

5.1.5 Quality Control Program

Full use of statistical process control (SPC) methodologies has facilitated the disciplined examination of manufacturing data. SPC methodology is being utilized on the manufacturing lines to learn more about our process and improve the manufacturing process.

To better understand the process of producing ACME components, a study of two (2) previous manufacturing runs (MCP-8 and PDI-1) was conducted. Processes such as mixing, tape casting and sintering were observed. This analysis was broken down into a series of steps. First, looking at the mixing portion of batch preparation, followed by tape casting, and finally sintering (if applied). Cause and Effect diagrams and individual batch analysis were used to identify key process parameters. Information gathered from the Fishbone analysis was then used to plan a designed experiment with the intention of optimizing the process by reducing variation and moving the process toward the target. Linear regression analysis was then used to determined functional relationships among variables. Next, an Analysis of Variance (ANOVA) and calculation of confidence intervals for each of the predicted dependent variables was performed. Finally, process control charts were developed for key process variables. Some information of this study can be found in Attachment 3.

Several conclusions were obtained from this study. For instance, properties of advanced ceramics change with the seasons. This means, ambient temperature and humidity are possible origins of the variations during mixing and tape casting operations. This may be related to the microstructure of the green tape or the slurry; but in fact, the study showed that room temperature and humidity had a big contribution to the quality of the final good (slurry and green tape). These variations may cause a variety of problems in manufacturing, enough reason to invest resources to isolate the material from the ambient condition. To alleviate room temperature effect, the doctor blade reservoir has been sealed.

A set of diagrams, forms, and tables were built during this study. As a tool for identifying possible cases of quality problems, a set of Cause-and-Effect diagrams were developed (see Attachment 3, Part I). These diagrams were developed by a group of engineers from the Manufacturing and Technology Development Departments. These diagrams are meant to find potential solutions to quality problems. Taking every single process data from previous run, we were able to perform a regression analysis and analysis of variance. The purpose for this analysis was to determine the effect of one or several factors to the final product. This analysis (see Attachment 3, Part II) helps us to identify what parameters to control so the process variations are minimized.

As mentioned before, the use of control charts (Attachment 3, Part III) helps us to better understand our processes. From these control charts, we were able to calculate our process capabilities and process performances. Process capability is an assessment of the stability of the process and the ability of the process to meet needed tolerance on critical characteristics. Two important indexes are calculated to measure those two quality properties: Cp and Cpk. Cp index measures the process variability. If Cp is less than 1, then the process is not capable; if Cp is equal to 1, then the process is marginally capable; if Cp is greater than 1, then the process is capable. On the another hand, Cpk measures how much the process is shifted from its specification. If the Cpk is equal to Cp, then the process is centered midway between its specification limits. In Table 9, our current process capability indexes are shown. Notice that these indexes were calculated previous to implementation of the new automated mixing system, the upgrade of the tape casters and sintering furnace. Furthermore, the new process parameters found have not been applied yet to production mode. Consequently, these indexes are going to be improved when we start production of the next MCFC.

Table 9: Process Capability Indexes

Manufacturing Process Capability Ratios: MCP8 Run

Component	Ratio	Process Parameter					
		Porosity	Mean Pore Size	Pre Assembled Thickness	Pre Assembled Shape	Weight Density	Lost of Ignition
Anode	Cp	0.46	1	1.1	1.9	n/a	n/a
	Cpk	0.4	0.75	0.9	1.7	n/a	n/a
	Comment	Expect to improve due to sintering furnace upgrade & Mixing Automation					
Cathode	Cp	0.61	9.43	1.16	2.65	n/a	n/a
	Cpk	0.45	8.55	0.77	1.85	n/a	n/a
	Comment	New product: Unsintered Cathode. More knowledge of process will improve ratios					
Matrix	Cp	0.7	1.7	0.62	3.02	n/a	n/a
	Cpk	0.52	0.74	0.59	0.66	n/a	n/a
	Comment	New product: HSA10 Matrix. More knowledge of process will improve ratios					
Electrolyte	Cp	n/a	n/a	0.37	1.57	0.42	0.37
	Cpk	n/a	n/a	0.33	0.37	0.39	0.3
	Comment	Expect to improve due to Tape Casters upgrade & Mixing Automation					

5.2 Implementation Plan for Manufacturing Improvement

By the year 2002 when our plant capacity is 15 MW, the following goals have to be met:

5.2.1 Lower Cost Matrix.- The primary objective is to replace the $54/Kg HSA-10 $LiAlO_2$ currently utilized for manufacturing stack matrices. Two lower cost alternatives are being pursued: (1) the formation of $LiAlO_2$ from low cost precursor materials, and (2) developing alternate Lithium Aluminate vendors.

5.2.2 Eliminate Carbon Beds.- Water-based casting formulations have been successfully developed for the matrices. Initial cell tests have been successful, but additional endurance testing is required. Powder dispensing techniques have been considered viable for distributing electrolyte powders during assembly for the future manufacturing plant to eliminate the casting solvents.

5.2.3 Increase manufacturing rates: In the past few months, Manufacturing has demonstrated 20 inches per minute on the existing equipment for both water-based and solvent-based tapes. The year 2005 casting rates for tall components could be increased to 30 inches per minute with the understanding that if additional zones were added to the commercial tape casters, casting rates in excess of 35 inches per minute could be achieved.

5.2.4 Decrease the number of assembled layers from seven to five tapes: Generally, cast thickness greater than 30 mils are difficult to dry without cracking. However, development efforts at M-C Power and Institute of Gas Technology are underway to meet this goal.

5.2.5 Increase manufacturing yields: From 67% for anodes and 87% for cathodes, to more than 92% and 95% for anodes and cathodes respectively. Matrix and electrolyte manufacturing yields to increase to more than 95%.

5.2.6 Reduce Non Repeat Part Cost to $154 per Kilowatt: By integrating the compression function of the clamping device into the pressure vessel structure, simplifying piping interconnections, minimizing instrumentation, and reusing high cost components between stacks.

5.2.7 Reduce Separator Plate costs to $193 per Kilowatt: By incorporating features into other components (so material and processing costs are reduced) and by using alternate materials.

5.2.8 Reduce the amount of acceptance testing prior to shipping: From 30 days to 22 days.

5.2.9 Increase Power Density: From 114 W/ft^2 to 149 W/ft^2. At a bench scale level, a power density of 179 W/ft^2 at 300 mA/cm^2 and 75% fuel utilization has been successfully demonstrated.

6. M-C POWER COST MODEL

The M-C Power Cost Model is a product of a study of the manufacturing cost study and planning activities. This cost model is being utilized as a tool to evaluate different alternatives ("what if" scenarios), to assists in identifying the elements that require the most improvements, and also to identify the current manufacturing costs. The input parameters to this cost model are:

- Number of cell per Stack
- Raw Materials
- Tape Casting
- Assembly
- Fixed Assets
- Square footage
- Design Factors
- Mixing
- Cutting
- Testing
- Overhead allocations
- Payroll

The output parameters of this cost model are:

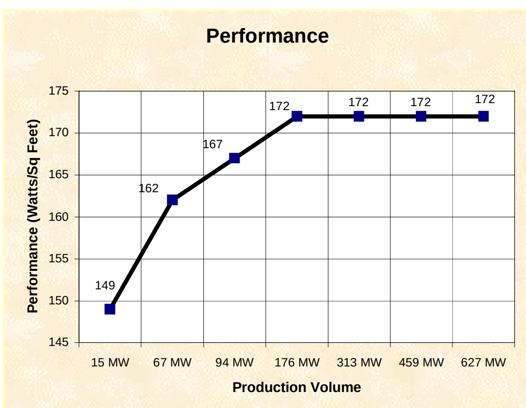
- Plant Capacity
- Cost Breakdowns
- Material
- Utility
- Square foot Requirement
- Headcount Requirement

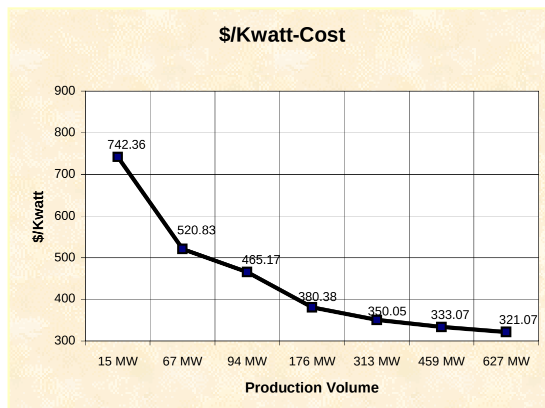
Every year, The Department of Energy audits M-C Power to evaluate its progress. One of the requirements is to facilitate a cost model for our commercialization plan. A summary sheet of the commercialization plan is shown in Table 10.

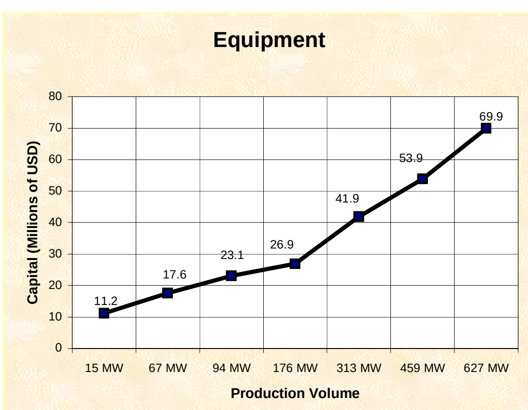
Table 10: Cost Model

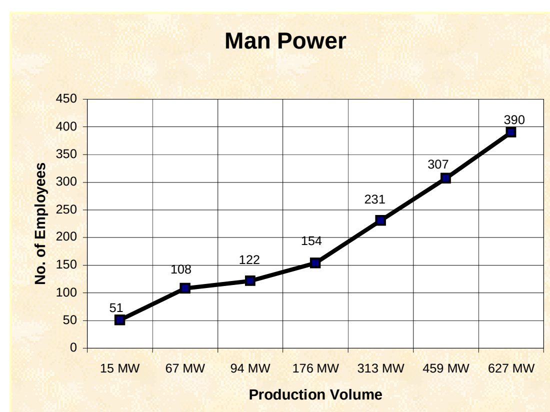
M-C POWER MCFC COMMERCIALIZATION FORECAST

	YEAR	2002	2003	2004	2005	2006	2007	2008
General	Volume (MW)	15	67	94	176	313	459	627
	Capital ($1M)	11.2	17.6	23.1	26.9	41.9	53.9	69.9
	Man Power	51	108	122	154	231	307	390
	$/KW	742	521	465	380	350	333	321
	Plant Square Ft. (1000's)	102	194	238	319	382	505	659
	Performance (W/Sq. Ft)	149	162	167	172	172	172	172
	Stacks Per Year	28	116	159	288	513	753	1029
Assets ($1M)	Mixing	0.98	0.98	1.47	1.96	3.43	4.41	5.88
	Tape Casting	2.90	2.90	4.40	5.80	10.20	13.10	17.40
	Sintering	1.77	1.77	3.54	3.54	7.08	8.85	12.39
	Cutting	0.82	1.64	2.46	3.28	5.74	9.02	11.48
	Assembly	1.36	2.36	3.36	4.36	7.36	10.36	14.36
	Testing	2.20	6.70	6.70	6.70	6.70	6.70	6.70
	Total	*10.03*	*16.35*	*21.93*	*25.64*	*40.51*	*52.44*	*68.21*









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The business plan for the year 2002 projects a plant production of 15 MW (See Attachment 4). This assumption is based on marketing studies done by people related to the energy sector. The computation of the projected cost per cell for that year shows that more than 50% of the total cost is assigned to materials. Inside this category, it is noticed that to reduce the cost, additional attention should be paid to manufacturing plates and non-repeat parts that together represent almost 50% of the total material cost.

Joining efforts between engineering design, manufacturing, technology development and others, a series of designs have been developed so in the long run the cost per cell drops from $742 US per Kilowatt to $321 US per Kilowatt in a period of 7 years.

Specifically, M-C Power has identified a separator plate and cell package engineering development path that consists of a progression of technology levels. Each is based on incremental improvements and specific component modifications. Between now and the year 2002, we will follow an approach to the separator plate and cell component developments that achieve the market entry power density and life goals. The separator plate design proved to be feasible is labeled as MOD-7. This is a cross flow configuration (how the fuel and oxidant gases are routed relative to each other) with rectangular active components, a flat Nickel Clad separator plate. This design reduces the cost because it:

- Simplifies design
- Simplifies rail tool design which reduces tooling cost.
- Eliminates the need for the press/anneal/press sequence formerly used for the corrugated separator plate.
- Simplifies active area component trimming and material handling steps.
- Improves matrix long term function by elimination of the cookie cutter effect of the opposing rails adjacent to the active area.
- Reduce component fit-up issues.
- Streamlines separator plate subassembly operations, and stack assembly.

M-C Power's overall approach for simplifying the hardware and reducing the cost of the non-repeat components per stack will be achieved by the following primary changes to the existing design:

1. Thermally insulating the stack to maintain the pressure vessel ambient temperature below 450 F degrees.
2. The clamping system is located in the "cold" zone within the pressure vessel (450 F degrees) and will include a set of chrome silicon mechanical springs (50 to 100 springs per stack).
3. Simplified end plates that minimize fabrication and machining steps.
4. Minimizing the stack instrumentation to reflect commercial requirements.
5. Minimize the length and optimizing the material of the power bus bars to extract power.
6. Thin gauge piping with no flanges for interconnecting process gases within the pressure vessel.

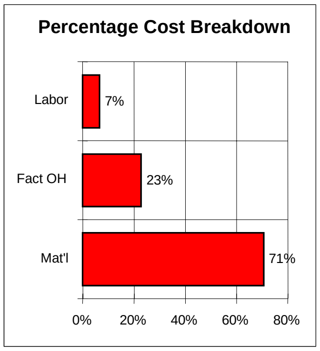
There is no significant technical risk associated with the design and fabrication of individual hardware components. This is because all the non-repeat hardware that will be used for market entry will already have been tested in a full area test facility. The ongoing objective of the non-repeat part task is to reduce cost by eliminating hardware and/or changing material selection for functional requirements in an improved operating environment.

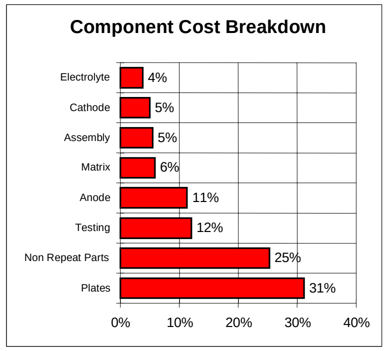
7. PLANT OF THE FUTURE

The business plan for the year 2004 forecasts a plant production capacity of 94 MW. This means M-C Power has to be able to support a production volume of 159 stacks [300 cells per stack @ 591 kW per stack] (Table 11). The vision of the factory where M-C Power will produce its MCFC's is shown in Figure 17. This factory will utilize automated material handling systems, auto-stackers, automated guided vehicles, and other machines and equipment that automate our manufacturing process. To develop the layout of the plant of the future, it was necessary to consider the following: 1) Minimize work in process 2) Minimize material flow congestion and 3) Minimize the material handling .

Table 11: M-C Power Cost Projection- Year 2004

Business Plan - 94 MW





Commercialization Plan

Plant Production	94 MW
Dollars / KiloWatt	465 $/kw

Features of 591 KW Stack

1. 167 Watt/SF performance
2. 591 KW Stack manufactured
3. 17 days for stack testing
4. 10 mandays for stack installation
5. 115 hours for assembly
6. $69,466 of non repeat parts cost
7. Batch Mixing, TC, & Sintering

Base Parameters

Cells Per Stack	300
Performance W/sq ft	167
Surface area sq ft	11.81
Stack Installation (mandays)	10
Weeks/Year	52
Workdays/Week	5
Holidays/Year	10
Downtime in Days	10
Plate man'f yields	100.0%
Volume Discounts	0%
Workdays/YEAR	240
Plant Utilization	65.75%

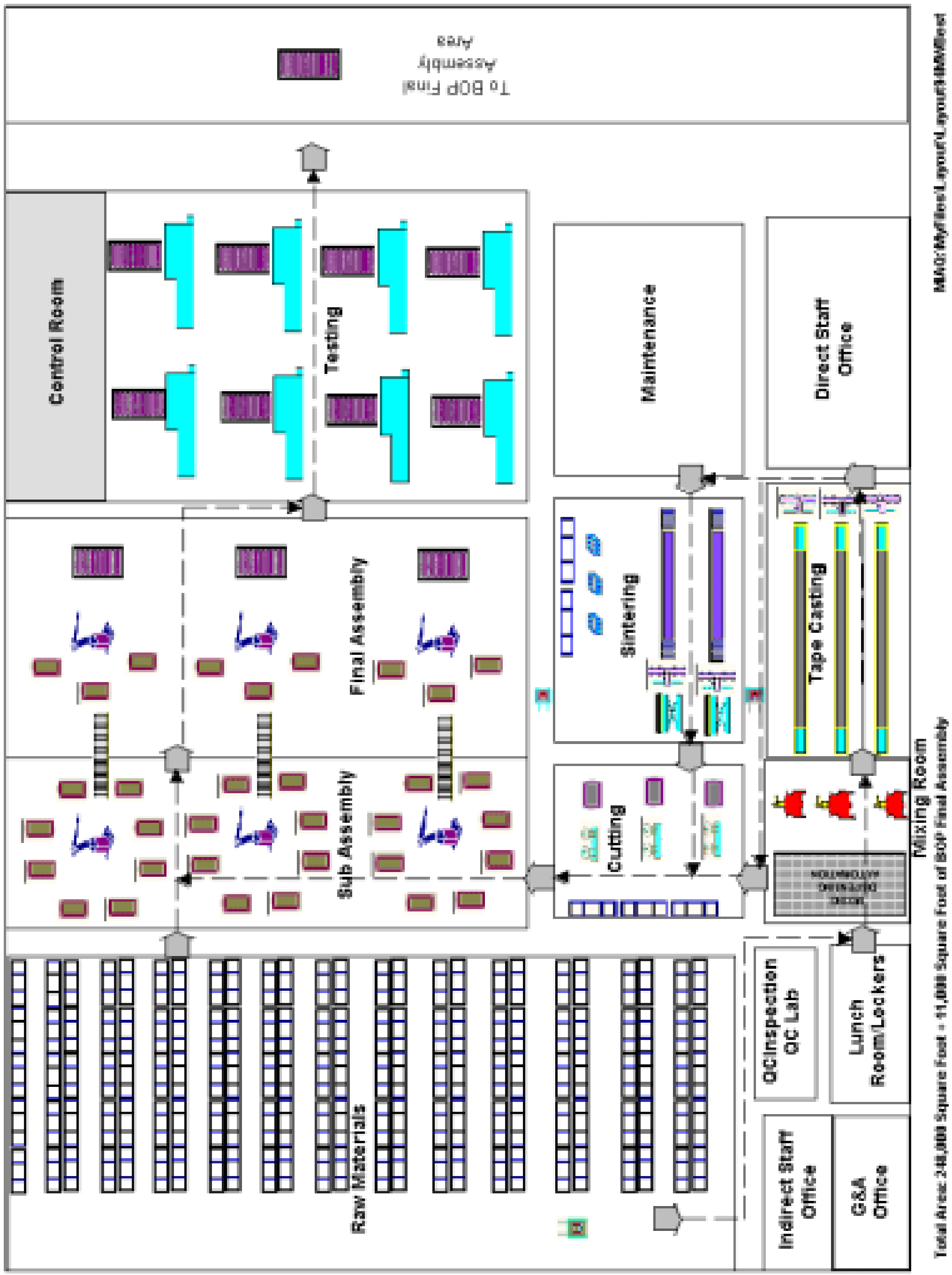
Capacity

KWatts per Stack	591
Surface Area Base MF	1
Total Cells / Year	47,700
Total Stacks / Year	159
Total Employees Needed	122

Dept. Summary	Shifts	Days
Mix & Tp Cast Dept	3	5
Sintering Dept	3	5
Cutting Dept	3	5
Assembly Dept	3	5
Testing Dept	3	7

Cost Breakdown	qty	mil	Mat'l	Labor	Fact OH	G & A	%	$ / kw
Anode	1	25.0	48.3	9.2	46.5	-	11.3%	52.8
Cathode	1	23.5	33.2	3.2	9.4	-	5.0%	23.3
Matrix	2	24.0	26.9	6.6	20.2	-	5.9%	27.3
Electrolyte	1	56.0	21.8	3.3	10.1	-	3.8%	17.9
Plates	1	16.0	285.5	0.0	0.0	-	31.2%	144.9
Anode CC	0	0.0	0.0	0.0	0.0	-	0.0%	0.0
Anode Flow Field(Foam)	1	11.6sf	0.0	0.0	0.0	-	0.0%	0.0
Cathode CC	0	12.0	0.0	0.0	0.0	-	0.0%	0.0
Cathode Flow Field(Shield)	1	12.0	0.0	0.0	0.0	-	0.0%	0.0
Non Repeat Parts			231.6	0.0	0.0	-	25.3%	117.5
Assembly			0.0	15.1	35.0	-	5.5%	25.4
Testing			0.0	22.6	87.8	-	12.1%	56.1
		Cost per Cell	$647	$60	$209	$0		
		Percentage	70.6%	6.6%	22.8%	0.0%		
		Dollar per Kwatt	**329 / kw**	**30 / kw**	**106 / kw**	**0 / kw**		

Figure 17. 94 MW MCP Plant Layout (Year 2004).



Attachment 1: Operation Sheets

Figure 1: Operation Sheets

OPERATIONS SHEET

PART NO: 100169 MCP-8 **PART NAME:** Anode **OPERATION:** 30

APPROVAL:

ISSUE DATE: 4-15-98 **DEPT. NAME:** Sintering

CHANGE CONTROL

Revision #	From	To	Rev. Date

Form Revised 2-6-98
D:\DOCUMENTS\PROCESS CHART\OperationSheets\anode\anodesint.30.wpd - 4-15-98 Page 1 of 10

Figure 1: Operation Sheets Continued

OPERATIONS SHEET

DEPT NAME: Sintering **DEPT NO:** 30 **OPER NO:** 30

PART NO: 100169 MCP-8 **PART NAME:** Anode

RAW MATERIALS & EQUIPMENT

Specifications	Rev	Qty
Raw Materials:		
Tape Cast 3% Chromium Anodes, Drawing# 100104		as req.
Equipment:		
Sintering Carrier (Specification 912)		1
Production Furnace (Specification 915)		1
8040 Building Fork Truck		1
4' X 7' Aluminum Clad Plywood Shelving Material		as req.
Shelving Transfer Carts		as req.
Scalpel		as req.
HEPA Type Vacuum Cleaner		1

Form Revised 2-6-98
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Figure 1: Operation Sheets Continued

OPERATIONS SHEET

DEPT NAME: Sintering **DEPT NO:** 30 **OPER NO:** 30

PART NO: 100169 MCP-8 **PART NAME:** Anode

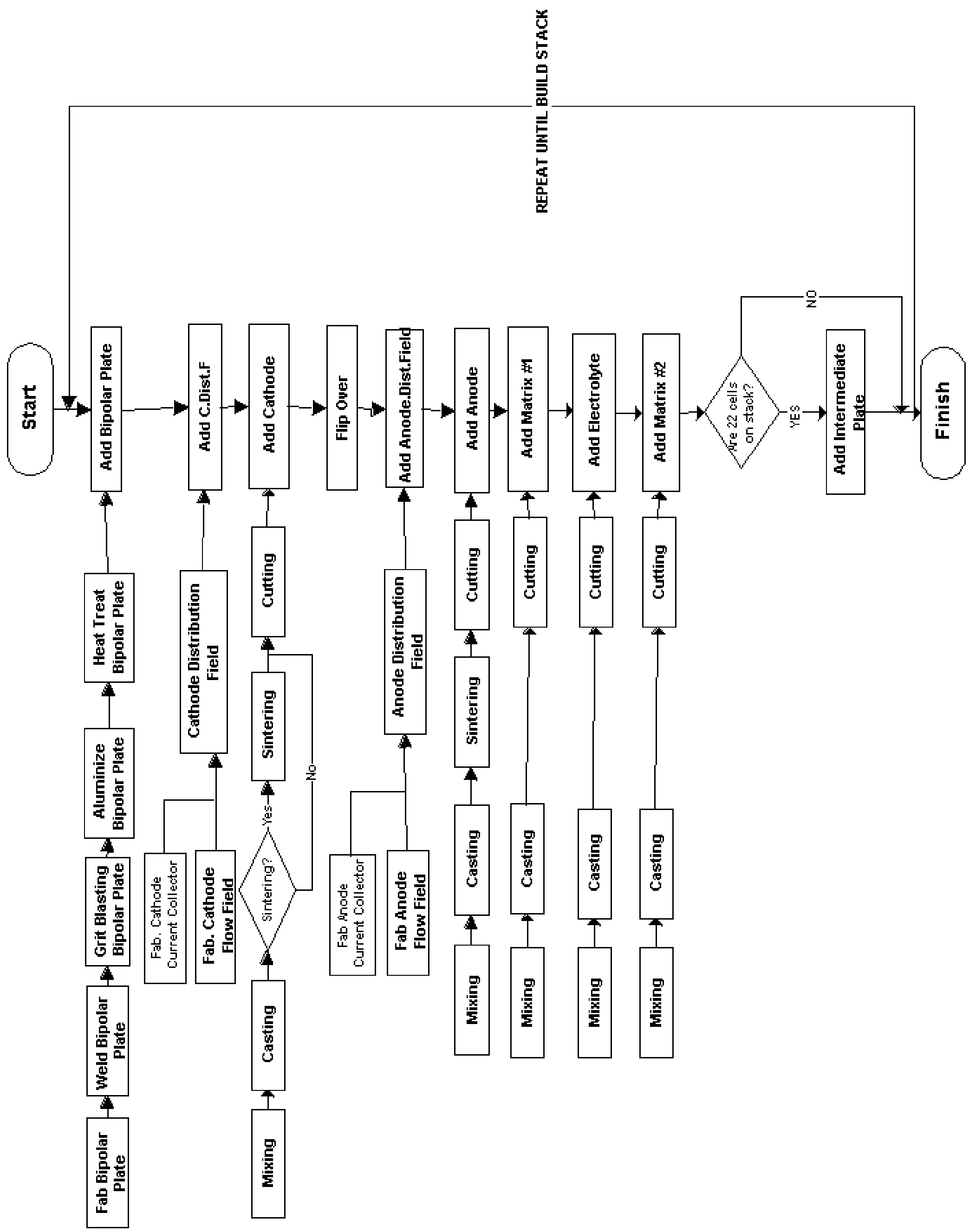
OPER NO.	INSTRUCTIONS	INITIAL
30.0	**Sintering Carrier Preparation**: Lightly sand inconel sheet with a plastic scouring pad or 600 grit sand paper as required to remove any bumps, debris, etc., if necessary, to insure a smooth flat surface.	
30.1	Turn carbon paint mixer (CPM) on.	
30.2	If CPM was off longer than 30 minutes prior to step 30.1, wait 5 minutes, otherwise wait 1 minute.	
30.3	Remove CPM fill port cover.	
30.4	If CPM was off longer than 30 minutes prior to step 30.1, perform steps 30.5 and 30.6, otherwise skip to step 30.7.	
30.5	Turn CPM dispensing pump on, and pump carbon paint back into the CPM for 30 seconds.	
30.6	Wait five (5) minutes.	
30.7	Pump desired quantity of carbon paint into the roller tray so that the roller tray reservoir is 75% full.	
30.8	Generously roll the carbon paint onto the sintering carrier so as to achieve a complete, uniform, and thick coverage and allow to dry for 30 minutes before use.	
30.9	Return unused carbon paint to CPM.	
30.10	Replace fill port cover on CPM when done.	
30.11	Turn CPM off.	
30.12	**Green Anode Insertion**: Replace furnace door entry wedge at start of shift and four (4) hours into shift.	

Form Revised 2-6-98

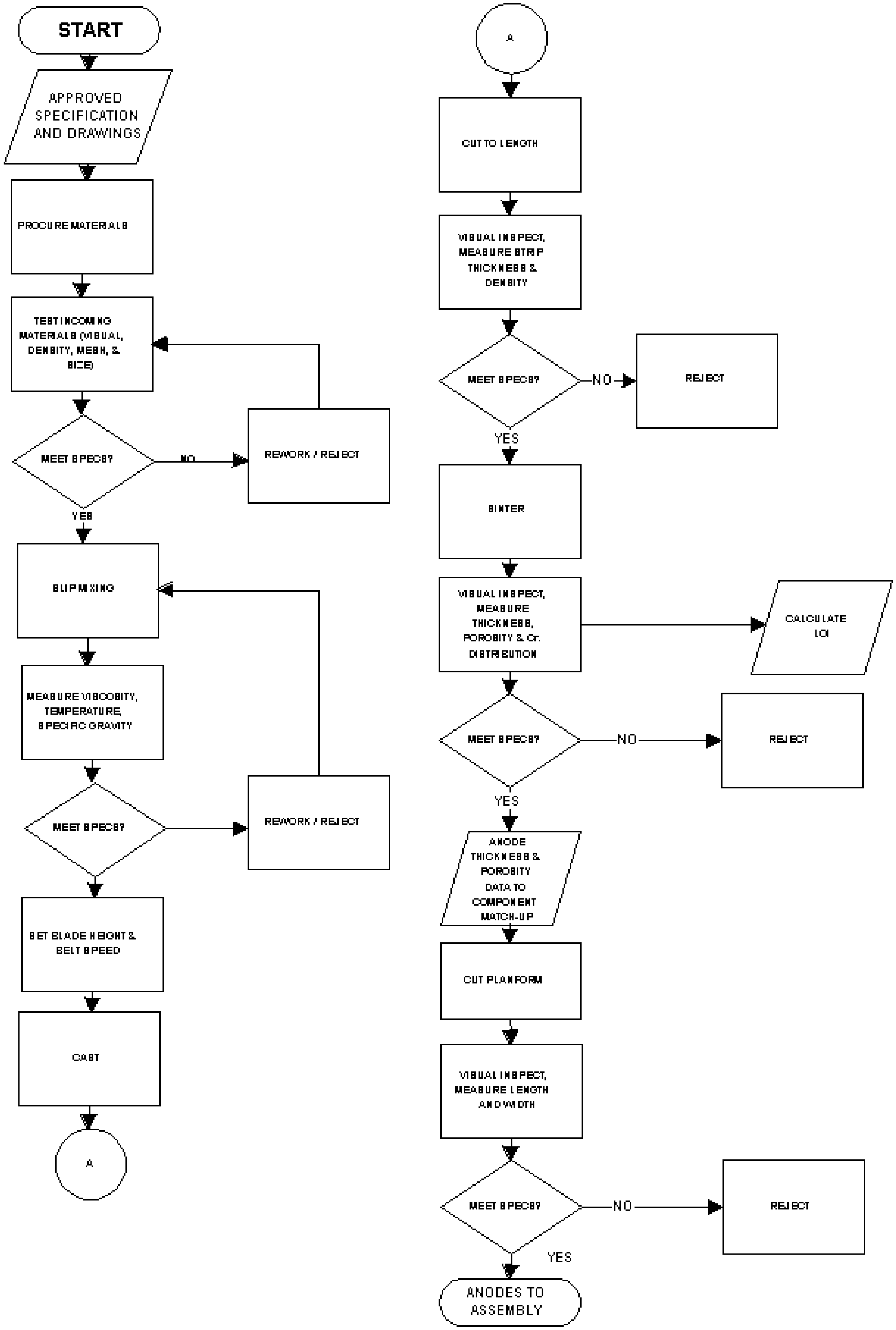
D:\DOCUMENTS\PROCESS CHART\OperationSheets\anode\anodesint.30.wpd - 4-15-98 Page 3 of 10

Attachment 2: MCFC Process Flow Charts

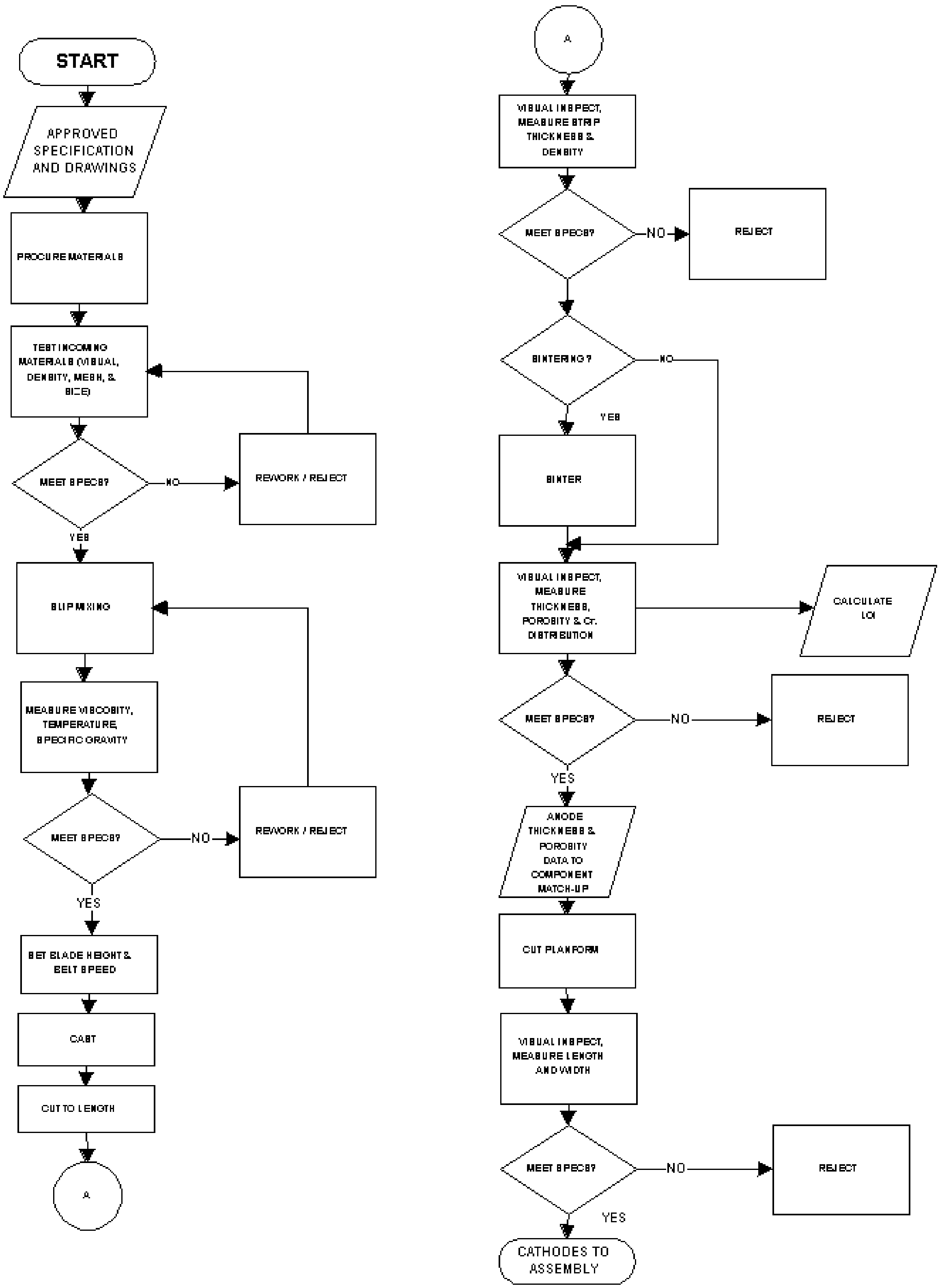
Molten Carbonate Fuel Cell Cell Sub Assembly Flow Chart



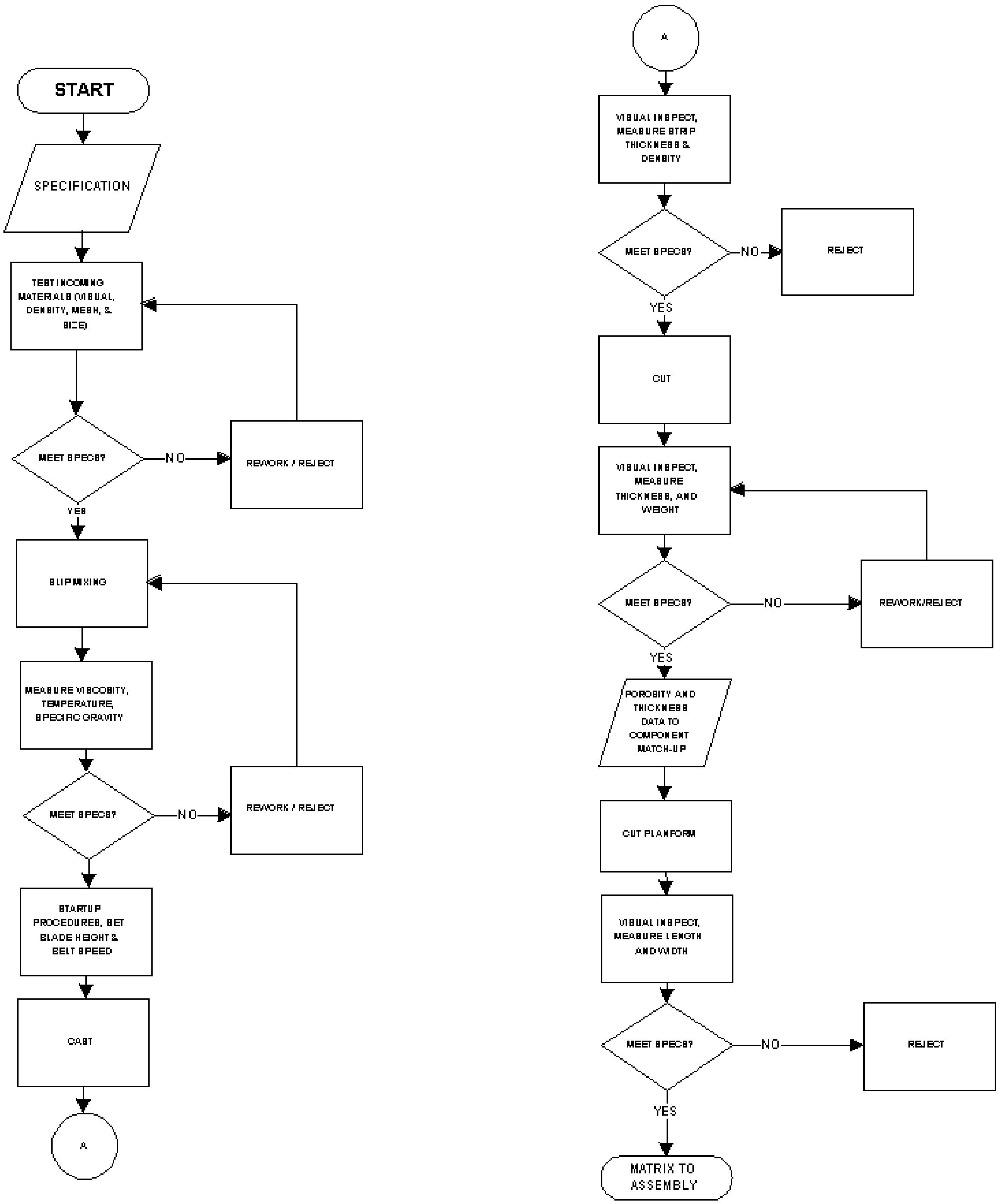
Anode Process Flow Chart



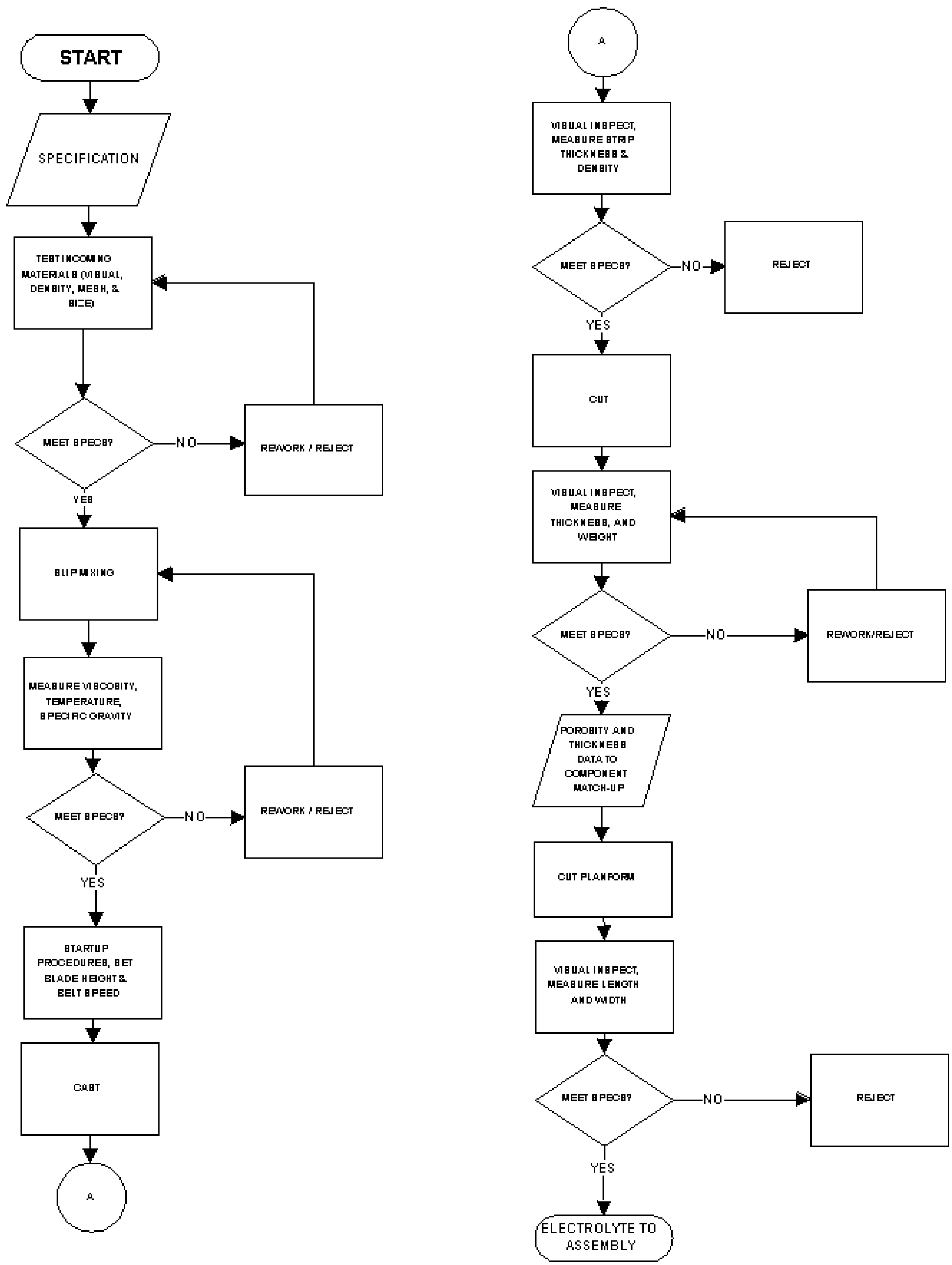
Cathode Process Flow Chart



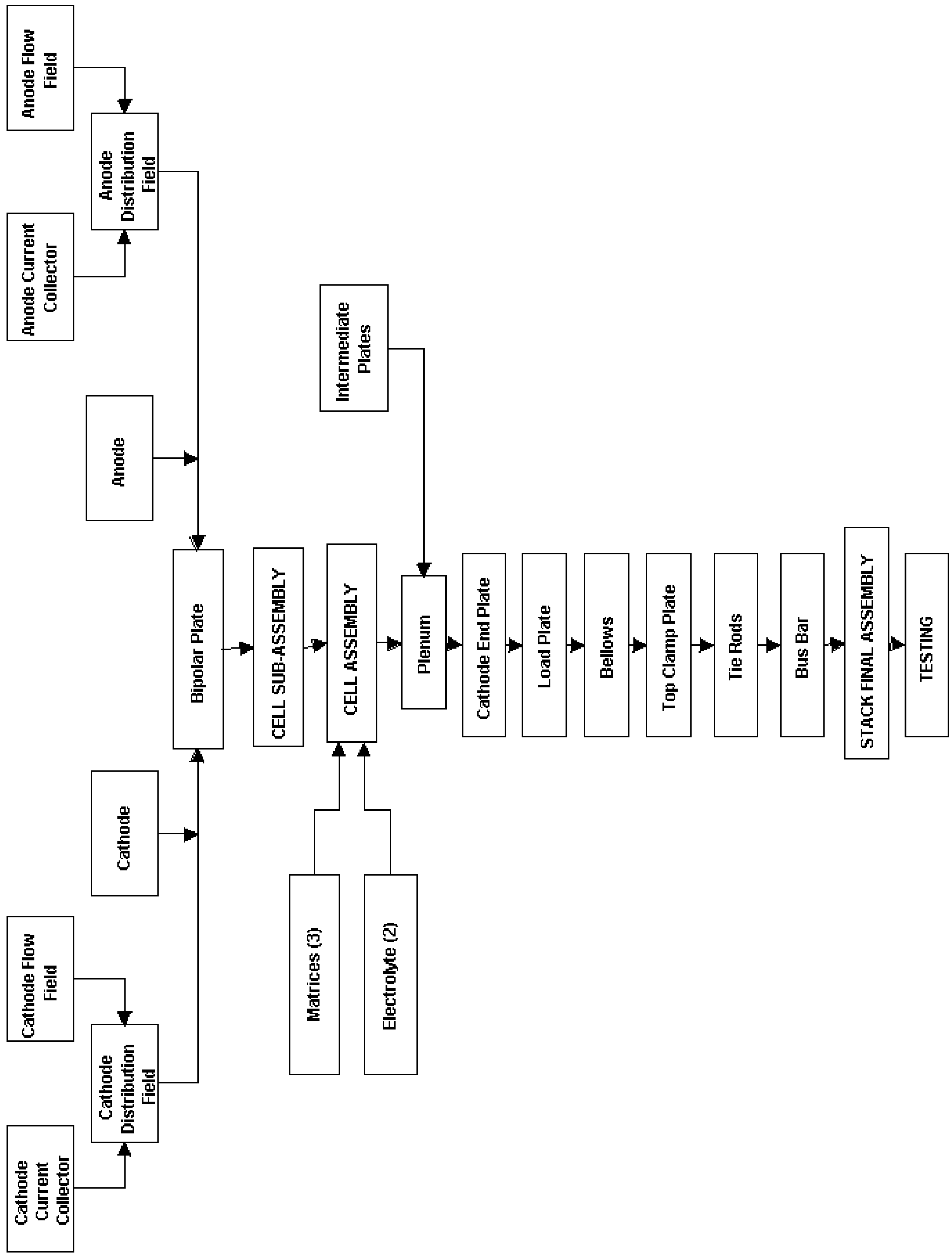
Matrix Process Flow Chart



Electrolyte Process Flow Chart



STACK ASSEMBLY PROCESS FLOW CHART

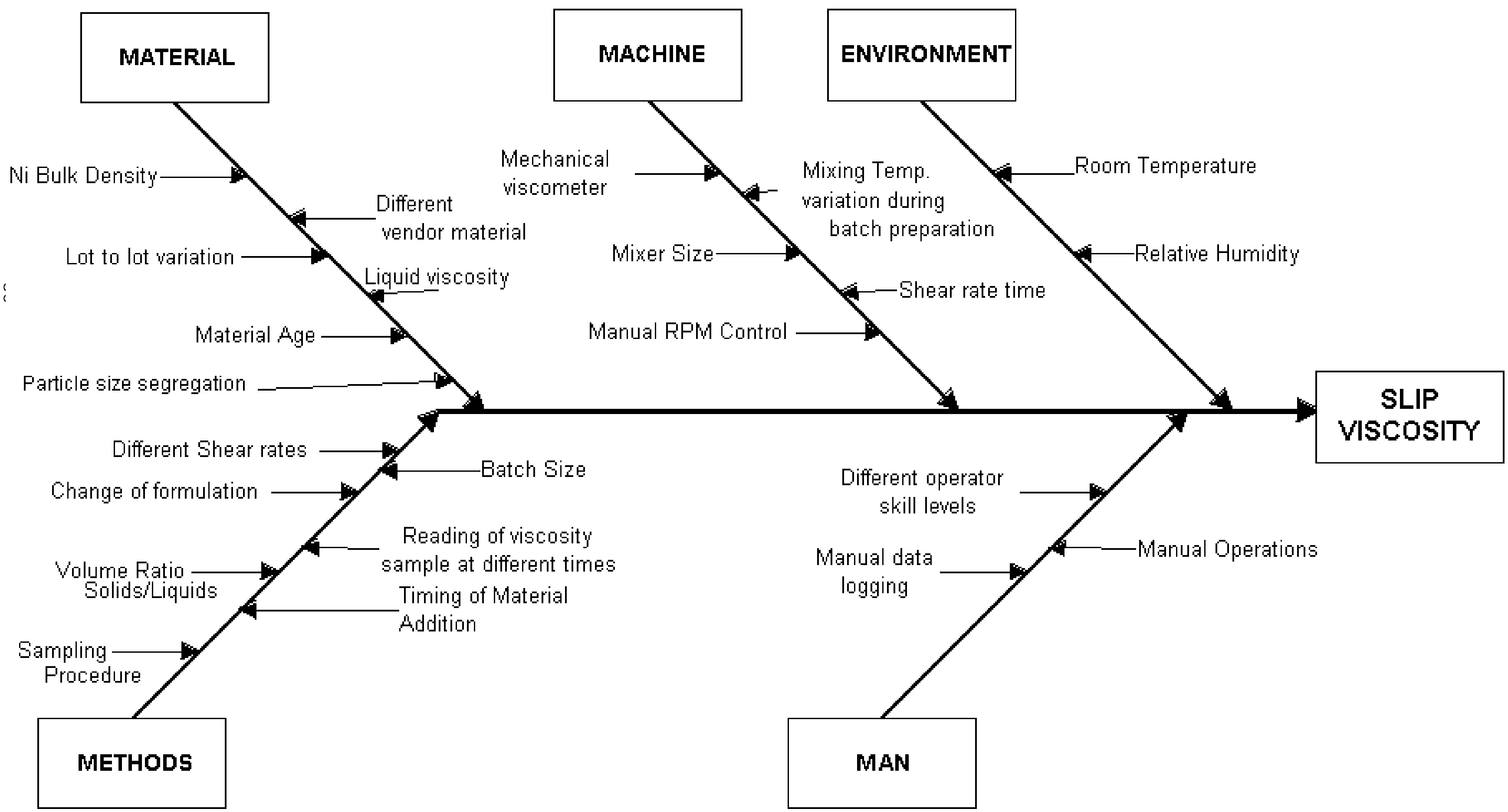


Attachment 3: ACME Process Parameter Analysis

ACME Process Parameter Analysis Output
ACME Control Charts (SPC)
Design of Experiment (DOE) Plan

Part I: Cause and Effect Diagrams (Fish bone Diagram)

Cause and Effect Diagram



Part II: Process Parameter Analysis (ANOVA/REGRESSION ANALYSIS RESULTS)

Anode Process Parameters Analysis

Geometric Porosity

Specifications (%)			Control Limits (%)		Regression Values (%)	
TARGET	LSL	USL	LTL	UTL	PREDICTED	95%CI	
50	47	53	48	52	50	46	53

Geometric Porosity (Por%)

VARIABLES TO CONTROL	TARGET	LTL	UTL	PREDICTED	95%CI		REGRESSION EQUATION	R Square	F Significant
DB Setting Inches (DB)-inch	0.0552	0.0530	0.0588	N/A	N/A	N/A	Por% = 90.02 - 454.29 * DB - 0.19 * TpreNI - 4835.26 * Cosine[Vis_F]/[TpreNi]^2	0.59	0.016
Pre Ni Add Slip Temp (F) (TpreNi)	75	73	77	N/A	N/A	N/A			
Final Adjusted 75 F Slip Viscosity (Visc_F)-cps	18329	17200	19000	17123	28095	6152	Visc_F = 66049.7 + 8.923*10 E-11* [Visc_3]^3 - 57502.26 * NiD	0.674	0
Bulk Density (NiD)-g/cc	0.89	0.87	0.91	N/A	N/A	N/A			
3 Hr.after Ni. Addition									
Adjusted 75F Visc (Visc_3)	29325	23325	35325	29325	16512	42132	Visc_3 = 5693 + 0.5176 * Visc_1	0.744	0
1 Hr.after Ni. Addition Adj.							Visc_1 = 374228.6 - 10482.4 * H_2O%	0.565	0
Temper. 75F Visc (Visc_1)	45650	34500	53427	45712	14708	76717			
H_2O mass% (H_2O%)	31.35	30.60	32.32	31.34	30.07	32.62	H_2O% = 111.7724 - 1.444 x Ni%	0.8553	0
Ni 287 mass% (Ni%)	55.70	55.39	56.24	N/A	N/A	N/A			
Pre Ni Add Slip Visc (cps) (Visc_PreNi)	2283.33	1976.80	2589.86	2291.96	1441.63	3126.07			
Sant 160 mass%(San)	0.90	0.70	1.12	N/A	N/A	N/A	Visc_PreNi = 4408.82 - 2340.14 x San	0.7354	0
Ethyl Clycol Mass% (EG)	1.24	1.07	1.35	N/A	N/A	N/A	Visc_PreNi = 6037.38 - 3018.1 x EG	0.7351	0
Methacel mass% (Meth)	2.422	2.35	2.53	N/A	N/A	N/A	Visc_PreNi = -8597.823 + 4492.85 x Meth	0.6963	0

MPS

Process Parameters for MPS

Specifications (u)			Control Limits (u)		Regression Values (u)		
TARGET	LSL	USL	LTL	UTL	PREDICTED	95%CI	
5.75	4.50	7.00	5.34	5.99	5.75	5.21	6.29

MPS (u)

VARIABLES TO CONTROL	TARGET	LTL	UTL	PREDICTED	95%CI		REGRESSION EQUATION	R Square	F Significant
HH#2 PV Temperature (C) (T_HH₂PV)	1081	1070	1090	N/A	N/A	N/A	MPS = -35.53 + 0.0382 * T_HH₂PV - 0.0176 * T_tilCast	0.706	0.0002
Time until casting (Hrs) (T_tilCast)	1	0.8	7.2	N/A	N/A	N/A			

Sintered Thickness

Process Parameters for Sintered Thickness

Specifications (Mils)			Control Limits (Mils)		Regression Values (Mils)		
TARGET	LSL	USL	LTL	UTL	PREDICTED	95%CI	
19.70	16.70	22.70	17.80	20.30	19.04	17.92	20.17

Sintered Thickness (Mils)

VARIABLES TO CONTROL	TARGET	LTL	UTL	PREDICTED	95%CI		REGRESSION EQUATION	R Square	F Significant
T/C Predicted Thickness Thickness (TC_Thk)-mils	25.0	24.0	26.0	25.0	23.4	27.0			
DB Setting Inches (DB)-inch	0.0552	0.0530	0.0588	N/A	N/A	N/A	Sint_Thk = 3.705 + 0.6 * TC_Thk	0.69	0
Final Adjusted 75 F Slip									
Viscosity (Visc_F) -cps	18329	17200	19000	17123	28095	6152	TC_Thk = 10.95 + 295.42 * DB - 0.0001123 * Visc_F	0.63	0

Sintered Shape

Process Parameters for Sintered Shape

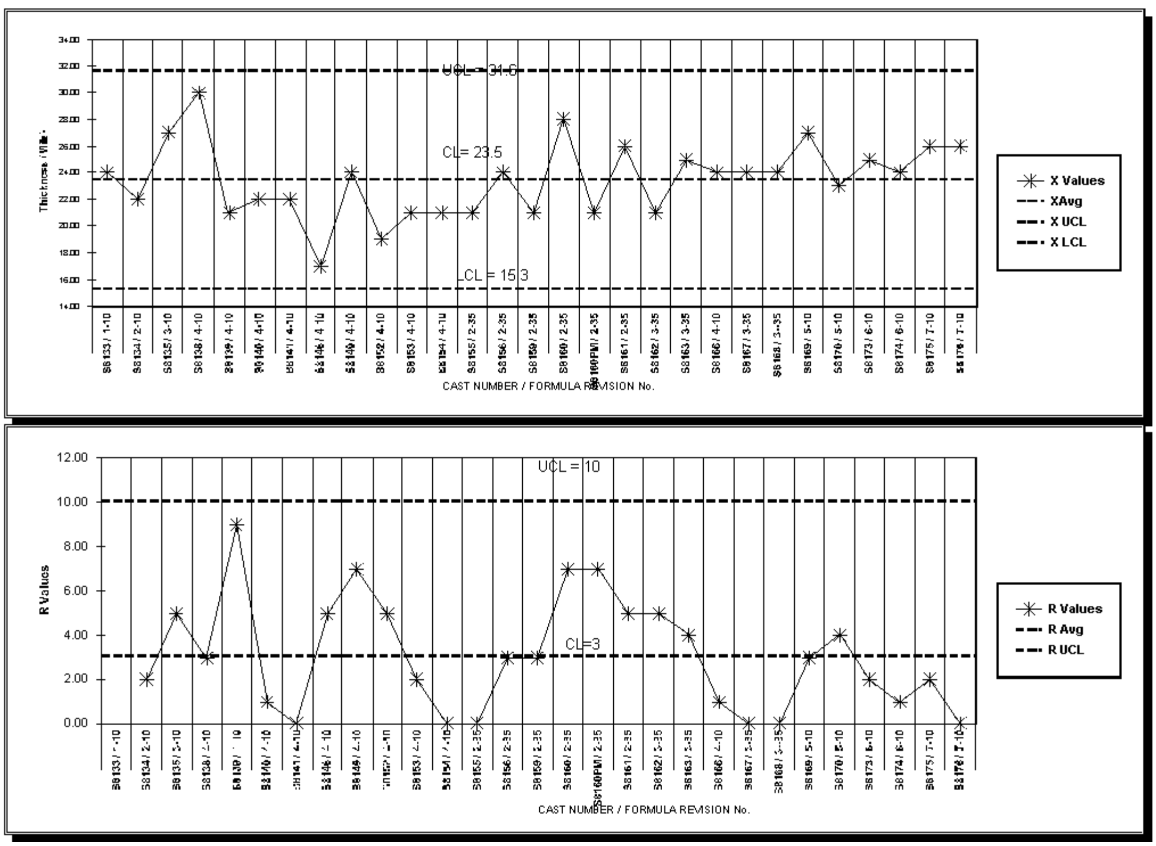
Specifications (mils)			Control Limits (mils)		Regression Values (mils)		
TARGET	LSL	USL	LTL	UTL	PREDICTED	95%CI	
0.000	-1.600	2.400	-0.600	0.600	0.070	-0.270	0.410

Sintered Shape (mm)

VARIABLES TO CONTROL	TARGET	LTL	UTL	PREDICTED	95%CI		REGRESSION EQUATION	R Square	F Significant
T/C Predicted Shape Thickness (TC_Shp)-MILS	0.025	-1.600	1.600	0.400	-1.200	0.340	Sint_Shp = 0.075 - 0.327 * TC_Shp	0.53	0.0014
Bulk Density (NiD)-g/cc	0.89	0.87	0.91	N/A	N/A	N/A			
							TC_Shp = 18.525-21.31*NiD	0.48	0.002

Part III: ACME Control Charts (Samples & Form)

Electrolyte Control Chart (Thickness)



Anode Control Chart

Manufacturing Department

Equipment: *Mixer*

Quality Characteristic (X): *Pre Ni Addition Slip Temperature*

Unit of Measurement: *Temp (F)*

Constants				
n	D4	A2	d2	D3
2	3.27	2.66	1.13	0

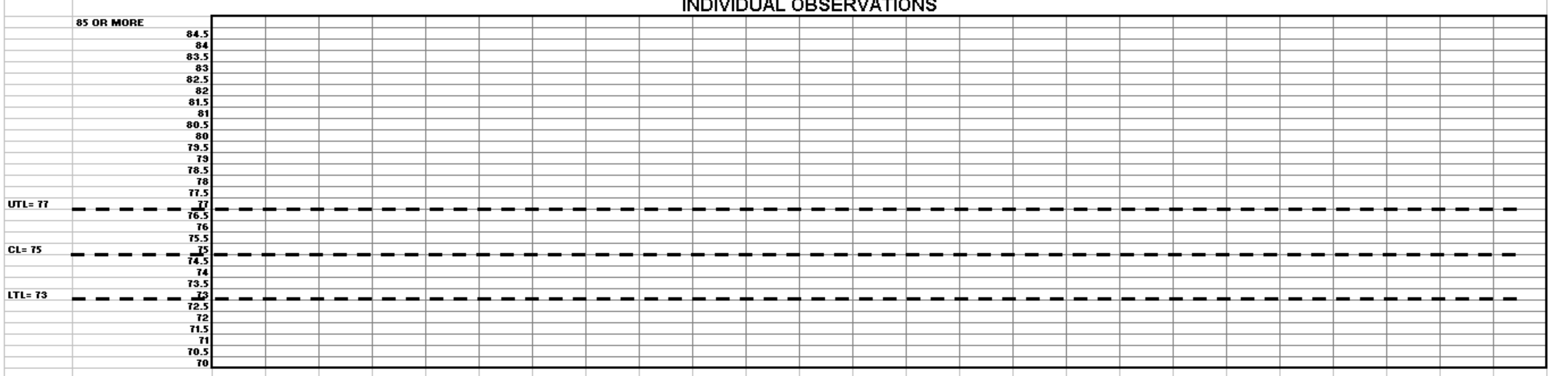
TARGETS					
Individual X			Moving Range		
Xbar	UTL	LTL	MR BAR	UTL	LTL
75	77	73	0.75	2.46	0

Process Notes

Date	
Time	
Slip #	
Temp (F)	
MR=Abs(Xcurrent - Xprevious)	

INDIVIDUAL MOVING RANGE CHART

INDIVIDUAL OBSERVATIONS



NOTE: Several forms of this type have been set for each of the main parameters correlated with the final output (Thickness, Shape, Porosity, Final Viscosity, MPS, etc). These main parameters were found through a statistical study. These forms are available if requested.

Part IV: Design of Experiment Plan

MATRIX DOE PLAN FOR TAPE CASTING

					NOISE	Season Humidity	Summer	Winter	Winter	Summer
						Daily RH/Room T	Random	Random	Random	Random
						Tape Caster No.	1	1	2	2
Trial No.	PROCESS PARAMETERS: Inner Array						Sample No			
	DB Setting (Inch)	T/C Zone 1 Temp (F)	T/C Zone 3 Temp (F)	T/C Zone 5 Temp (F)	Slip Delivery System Type		1	2	3	4
							Results			
1	Low	Low	Low	Low	1					
2	Low	Low	Low	High	2					
3	Low	High	High	Low	1					
4	Low	High	High	High	2					
5	High	Low	High	Low	2					
6	High	Low	High	High	1					
7	High	High	Low	Low	2					
8	High	High	Low	High	1					
Level 1: Low	Low	Low	Low	Low	1					
Level 2: High	High	High	High	High	2					
Comments										

Note:
* Two columns are available for interaction between any pair of parameters or extra parameters to control
** Since the tape caster will be run at 20 IPM, the different parameters levels will be determined at a later date
*** Results to record consist of Shape, Thickness, Corrected Weight Density, and Loss on Ignition
*** Delivery System 1= 43" slotted delivery System 2= Dual Feed Delivery System

DOE PLAN FOR MIXING

					NOISE	RPM Variation	Random	random	random	Random
						Slip Temperature	Random	random	Random	random
						Mixer Type	Yellow	Yellow	Red	Red
Trial No.	PROCESS PARAMETERS: Inner Array						Sample No			
	Solvent/Powder Weight Ratio	Li/Na Bulk Density (g/cc)	Dispersant/Powder Weight Ratio	Powder Addition Time Per Powder Weight(min/Kg)	Qmill Time (hrs)	Binder/Powder Weight Ratio	1	2	3	4
							Results			
1	0.04	Low	0.005	0.8	0.75	0.33				
2	0.04	Low	0.005	2	1.5	0.4				
3	0.04	High	0.01	0.8	0.75	0.4				
4	0.04	High	0.01	2	1.5	0.33				
5	0.08	Low	0.01	0.8	1.5	0.33				
6	0.08	Low	0.01	2	0.75	0.4				
7	0.08	High	0.005	0.8	1.5	0.4				
8	0.08	High	0.005	2	0.75	0.33				
Level 1: Low	0.04	Low	0.005	0.8	0.75	0.33				
Level 2: High	0.08	High	0.01	2	1.5	0.4				
Comments	Powder Amount Constant	By Hall Flow Meter	Powder Amount Constant			Powder Amount Constant				

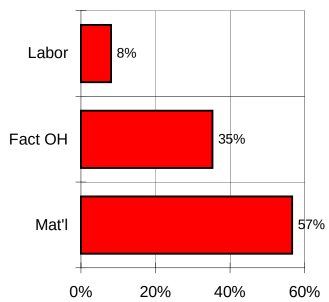
Note:
* One column is available for interaction between any pair of parameters
** All the other process parameters are maintained constant as specified in Revision No. 7.
*** Results to record consist of Viscosity and slip density

Similar Plans were developed for the other ACME components. These plans are available if requested

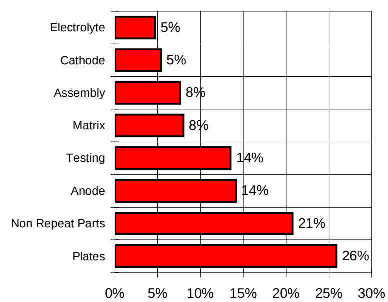
Attachment 4: Cost Model (2002 Year Case)

Business Plan - 15 MW

Percentage Cost Breakdown



Component Cost Breakdown



Commercialization Plan

Plant Production	15 MW
Dollars / KiloWatt	742 $/kw

Features of 527 KW Stack

1. 149 Watt/SF performance
2. 527 KW Stack manufactured
3. 22 days for stack testing
4. 10 mandays for stack installation
5. 115 hours for assembly
6. $81,245 of non repeat parts cost
7. Batch Mixing, TC, & Sintering

Base Parameters

Cells Per Stack	300
Performance W/sq ft	149
Surface area sq ft	11.81
Stack Installation (mandays)	10
Weeks/Year	52
Workdays/Week	5
Holidays/Year	10
Downtime in Days	10
Plate man'f yields	100.0%
Volume Discounts	0%
Workdays/YEAR	240
Plant Utilization	65.75%

Capacity

KWatts per Stack	527
Surface Area Base MF	1
Total Cells / Year	8,400
Total Stacks / Year	28
Total Employees Needed	51

Dept. Summary	Shifts	Days
Mix & Tp Cast Dept	3	5
Sintering Dept	3	5
Cutting Dept	3	5
Assembly Dept	3	5
Testing Dept	3	7

Cost Breakdown

	qty	mil	Mat'l	Labor	Fact OH	G & A	%	$ / kw
Anode	1	25.0	48.3	19.4	116.5	-	14.1%	104.8
Cathode	1	23.5	33.2	8.0	29.1	-	5.4%	40.0
Matrix	2	24.0	26.9	16.2	61.1	-	8.0%	59.3
Electrolyte	1	56.0	21.8	8.2	31.4	-	4.7%	34.9
Plates	1	12.0	337.8	0.0	0.0	-	25.9%	192.3
Anode CC	0	0.0	0.0	0.0	0.0	-	0.0%	0.0
Anode Flow Field (Foam)	1	11.6sf	0.0	0.0	0.0	-	0.0%	0.0
Cathode CC	0	12.0	0.0	0.0	0.0	-	0.0%	0.0
Cathode Flow Field (Shield)	1	12.0	0.0	0.0	0.0	-	0.0%	0.0
Non Repeat Parts			270.8	0.0	0.0	-	20.8%	154.2
Assembly			0.0	21.4	77.8	-	7.6%	56.5
Testing			0.0	32.1	144.1	-	13.5%	100.3
		Cost per Cell	$739	$105	$460	$0		
		Percentage	56.7%	8.1%	35.3%	0.0%		
		Dollar per Kwatt	**421 / kw**	**60 / kw**	**262 / kw**	**0 / kw**		